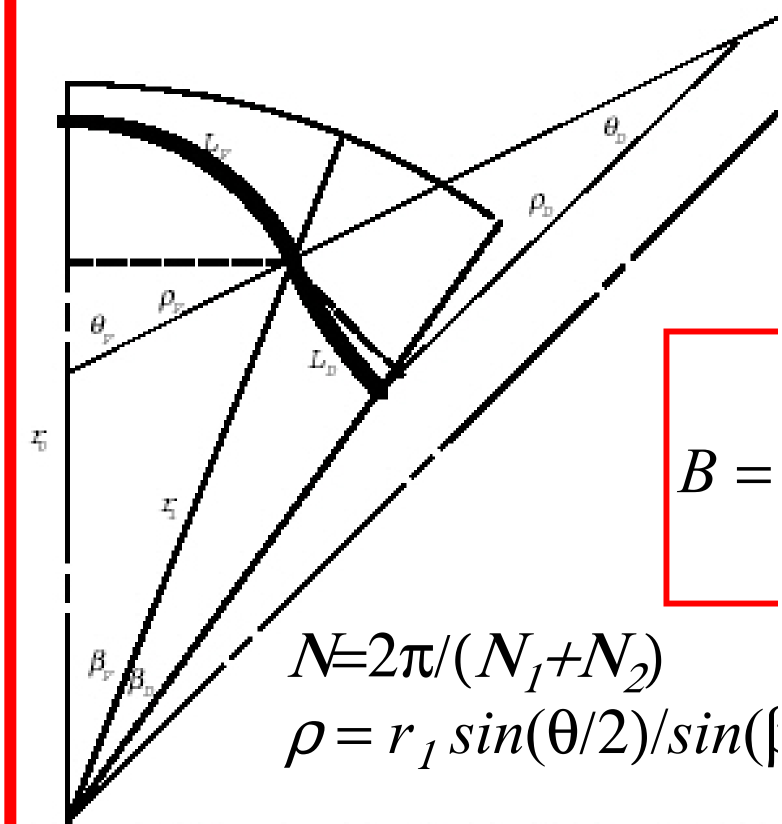
Wide applications of the Non-Scaling FFAG's and a report from the latest FFAG workshop at TRIUMF

- **Introduction: what is the scaling and non-scaling FFAG?**
- **A little bit of chronology.**
- **Possible wide applications with few examples.**
- **FFAG's in the BNL? A team of experts had already been formed.**
- **The major results from the TRIUMF workshop.**
- **Short report from many presentations by: E. Keil, S. Berg, R. Palmer, S. Ruggiero, Al Garren, C. Johnstone, S. Koscielniak, M. Craddock, A. Sessler, Y. Morri, F. Shouxian, D. Kalchev, T. Suzuki, S. Machida, S. Kahn, G. Clark.**

What is the SCALING FFAG ?

MURA-KRS-6
November 12, 1954
K. R. Symon: The FFAG SYNCHROTRON – MARK I

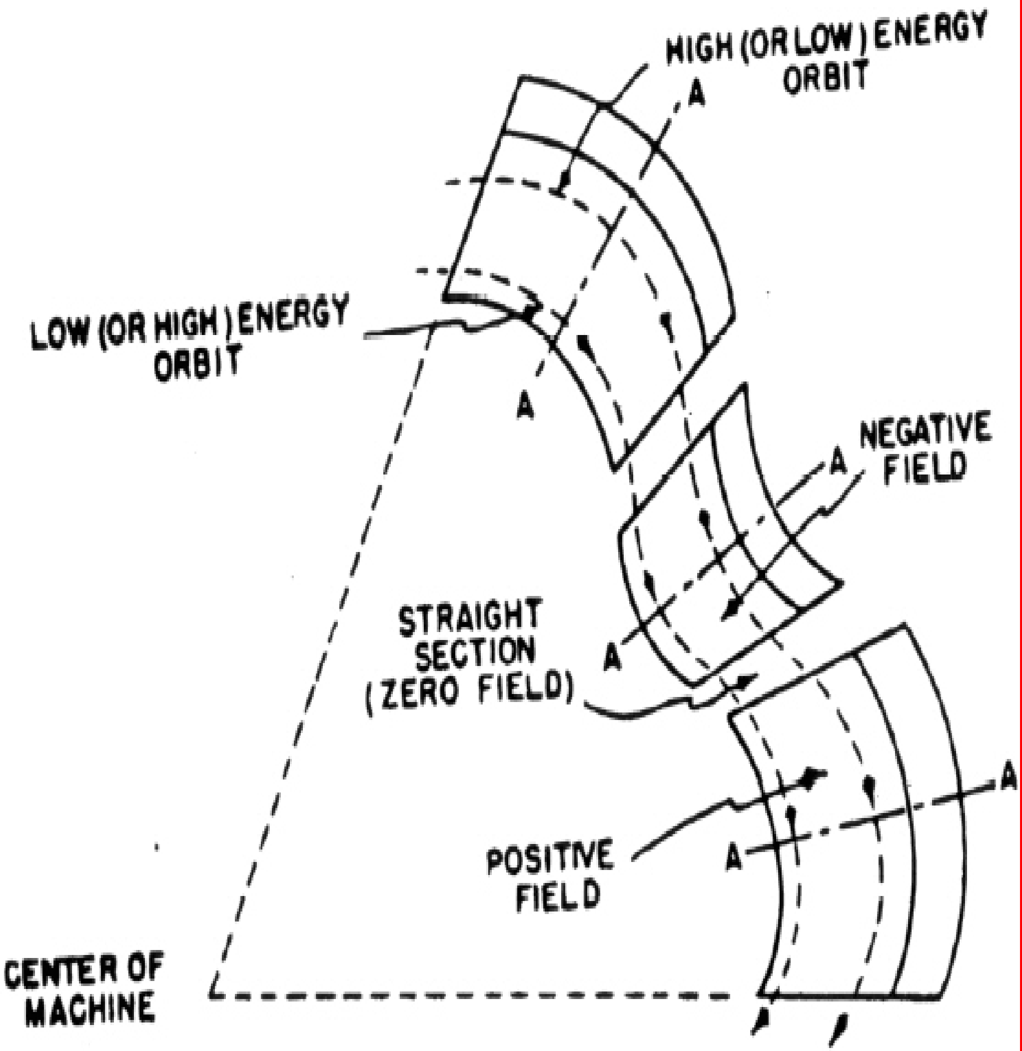


$B =$

$N = 2\pi/(N_1+N_2)$

$\rho = r_1 \, sin(\theta/2)/sin($

Figure 1: Closed orbit of a triplet focusing FF
half cell; a half of F magnet, D magnet of one
half straight section, is depicted.



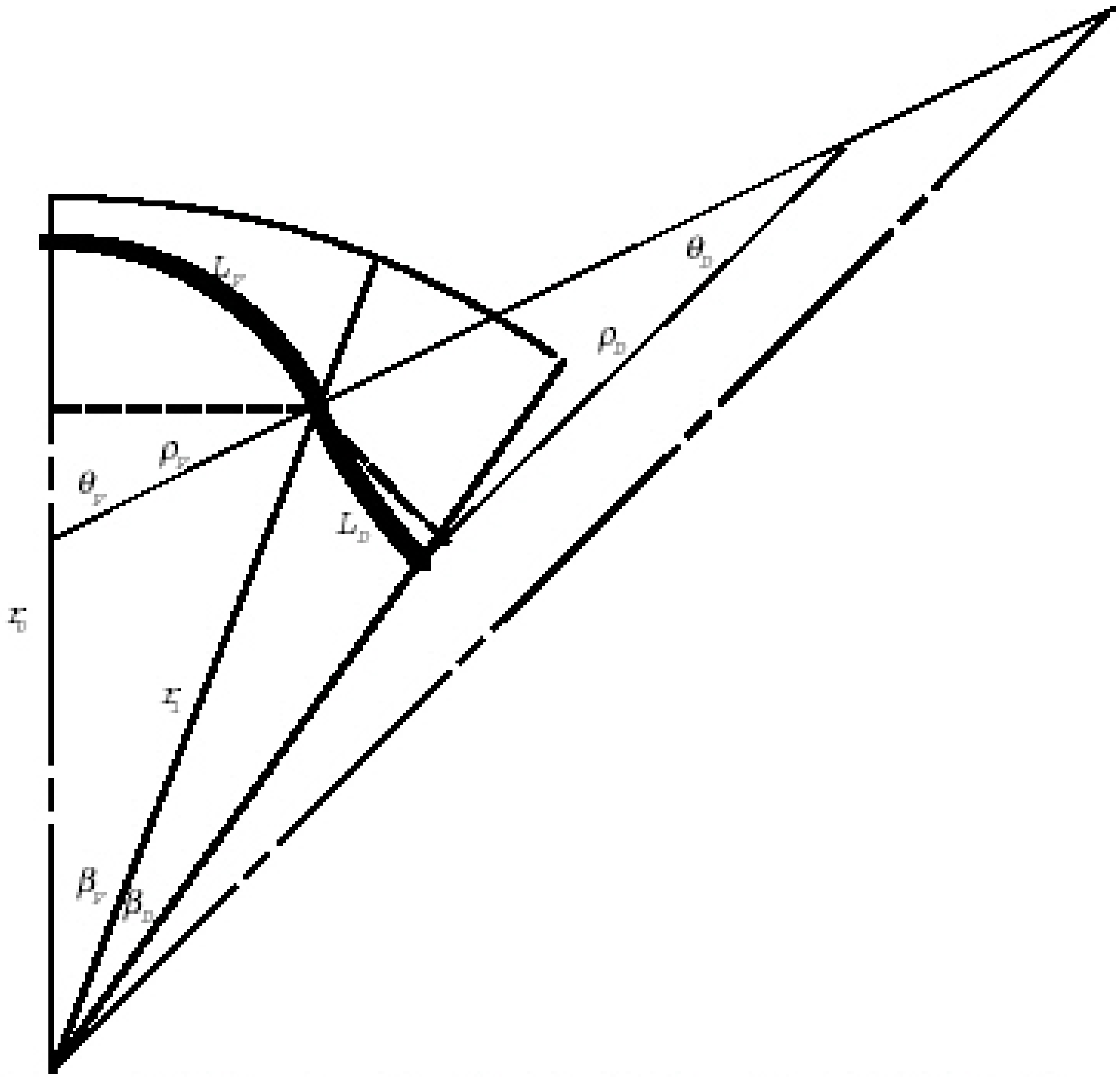


Figure 1: Closed orbit of a triplet focusing FFAG. Only a half cell; a half of F magnet, D magnet of one side, and a half straight section, is depicted.

Original FFAG Phys. Rev. article (1956)

PHYSICAL REVIEW VOLUME 103, NUMBER 6 SEPTEMBER 15, 1956

Fixed-Field Alternating-Gradient Particle Accelerators*

K. R. SYMON,† D. W. KERST,‡ L. W. JONES,§ L. J. LASLETT,‖ AND K. M. TERWILLIGER§
Midwestern Universities Research Association

(Received June 6, 1956)

It is possible, by using alternating-gradient focusing, to design circular accelerators with magnetic guide fields which are constant in time, and which can accommodate stable orbits at all energies from injection to output energy. Such accelerators are in some respects simpler to construct and operate, and moreover, they show promise of greater output currents than conventional synchrotrons and synchrocyclotrons. Two important types of magnetic field patterns are described, the radial-sector and spiral-sector patterns, the former being easier to understand and simpler to construct, the latter resulting in a much smaller accelerator for a given energy. A theory of orbits in fixed-field alternating-gradient accelerators has been worked out in linear approximation, which yields approximate general relationships between machine parameters, as well as more accurate formulas which can be used for design purposes. There are promising applications of these principles to the design of fixed-field synchrotrons, betatrons, and high-energy cyclotrons.

INTRODUCTION

ALTERNATING-GRADIENT (AG) focusing[1] provides a high degree of stability for both radial and vertical modes of betatron oscillations in circular magnets vary in the same way with radius but with alternating signs (or in certain cases alternating magnitudes). Since the orbit in the reverse field magnet bends away from the center, the machine is considerably

In Part I of this paper we discuss the radial- and spiral-sector types of FFAG accelerator in detail. In Part II the theory of particle trajectories in FFAG machines is developed. Part III contains a description of a 10-Bev radial-sector synchrotron, a 20-Bev spiral-sector synchrotron, and FFAG betatrons and cyclotrons.

I. TYPES OF FFAG DESIGN

1. Radial-Sector Type

Circular particle accelerators with radial sectors can be built with the high-energy orbits at the outer edge of the machine and the injection orbits at the inside edge, or vice versa. This discussion assumes that the is of course determined by the necessity for preserving stability of the vertical betatron oscillations. Some vertical focusing and radial defocusing occur because the orbits are scalloped and do not cross the magnet edges at right angles. In machines in which the number of sectors is large and the effects of orbit scalloping small, the negative-field magnet can be made no shorter than about $\frac{2}{3}$ of the positive-field magnet if we wish to preserve vertical stability. This means that, neglecting

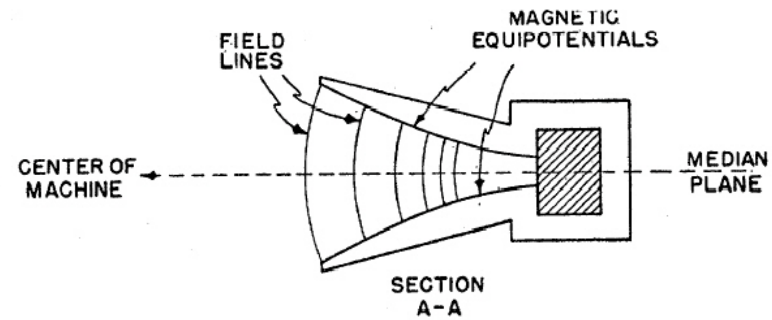


FIG. 1. Vertical section through positive or negative radial-sector magnets.

[4] Terwilliger, Jones, Kerst, and Symon, Phys. Rev. 98, 1153(A) (1955). This had been pointed out independently by G. Miyamoto, Tokyo University, Tokyo, Japan, at a meeting of the Physical Society of Japan in April, 1952 (private communication).

[5] L. H. Thomas, Phys. Rev. 54, 580, 588 (1938).

K.R. Symon

$C = 2\pi r_o \sim 612$ m

$p_{end} = 10.9$ GeV/c $\delta p/p_c = +/-98$ %

$p_{initial} = 97.0$ MeV/c

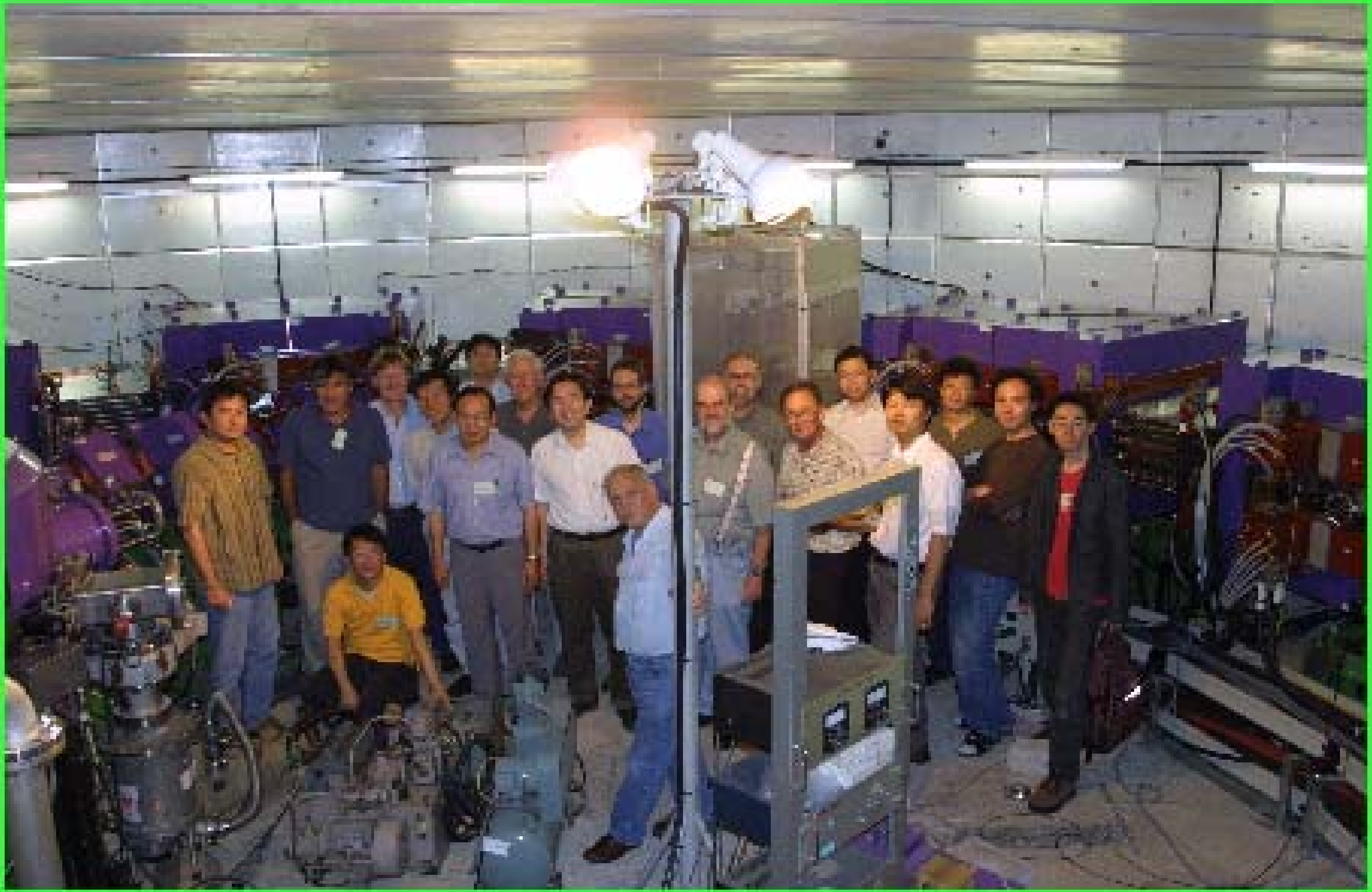
$p_c = 5.5$ GeV/c

TABLE II. Physical dimensions of a radial sector accelerator. Subscript 0 refers to maximum energy, subscript i refers to injection.

$E_0 = 10$ Bev	$E_i = 5$ Mev	proton kinetic energy
$r_0 = 97.3$ m	$r_i = 95.0$ m	synchrotron radius
$B_0 = 20\,000$ gauss	$B_i = 200$ gauss	magnet guide field
$\rho_0 = 18.2$ m	$\rho_i = 17.8$ m	radius of curvature
$Z_0 = 3.0$ cm	$Z_i = 15.0$ cm	vertical semiaperture
$\boxed{r_0 - r_i = 2.3 \text{ m}}$	radial aperture ← **Orbit offsets**	
$E_t = 12$ Bev	transition energy	
$Z_i = 2.5$ cm	vertical semiheight of injected beam	
$\delta_i = \pm 0.001$ radian	angular spread of injected beam	
$p = 5 \times 10^{-6}$ mm Hg	pressure in the vacuum chamber	

150 MeV FFAG at KEK

FFAG Accelerator Workshop; FFAG03



fast proton FFAG @KEK (2001)

Dejan Trbojevic
September 30, 1999
Montauk, Long Island
Muon Collider Workshop

FFAG Lattice Presented as a Trigonometrical Problem

- Introduction
- Why the K.R. Symon FFAG proposal finally got the attention after 44 years (1954)??
- Basic Parameters - trigonometry
- An Example
- Possible Improvements

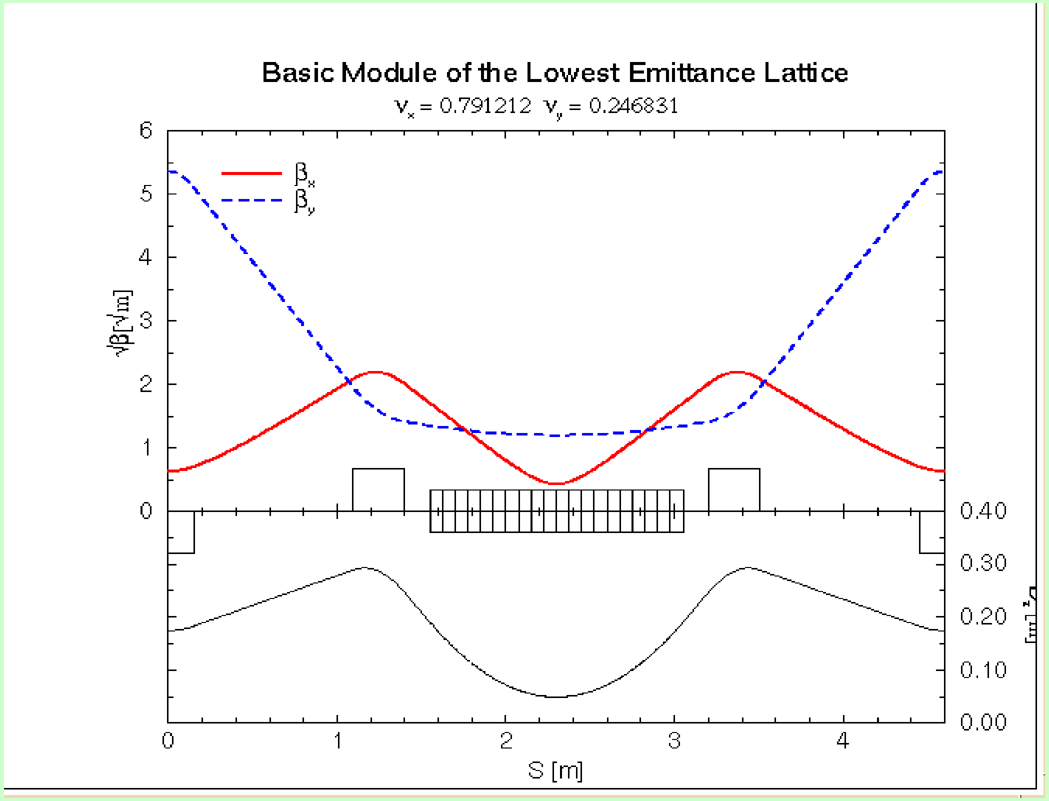
What are the basic parameters?

- Required Range of Energies (or dp/p)
  - the “central” energy or momentum p_o is in two examples presented later set to 10 GeV or 15 GEV. The acceleration would be possible from 5 GeV up to 15 GeV or from 10 GeV up to 15 GeV.
  - Aperture limitation is defined by the maximum value of the DISPERSION function: **Δx < D_x * dp/p** < +/- 35 mm
    - if the 0.5 < dp/p < 1.5 then:
    - **D_x < 70 mm**
- Why is the Minimum of the < H > function relevant?
  - The normalized dispersion amplitude corresponds to the <H>$^{1/2}$!!!

$$\Delta C = \left[\oint_C \frac{D(s)}{\rho} ds \right] \delta \quad where\ \delta = \frac{\Delta p}{p}.$$

The minimum emittance lattice:

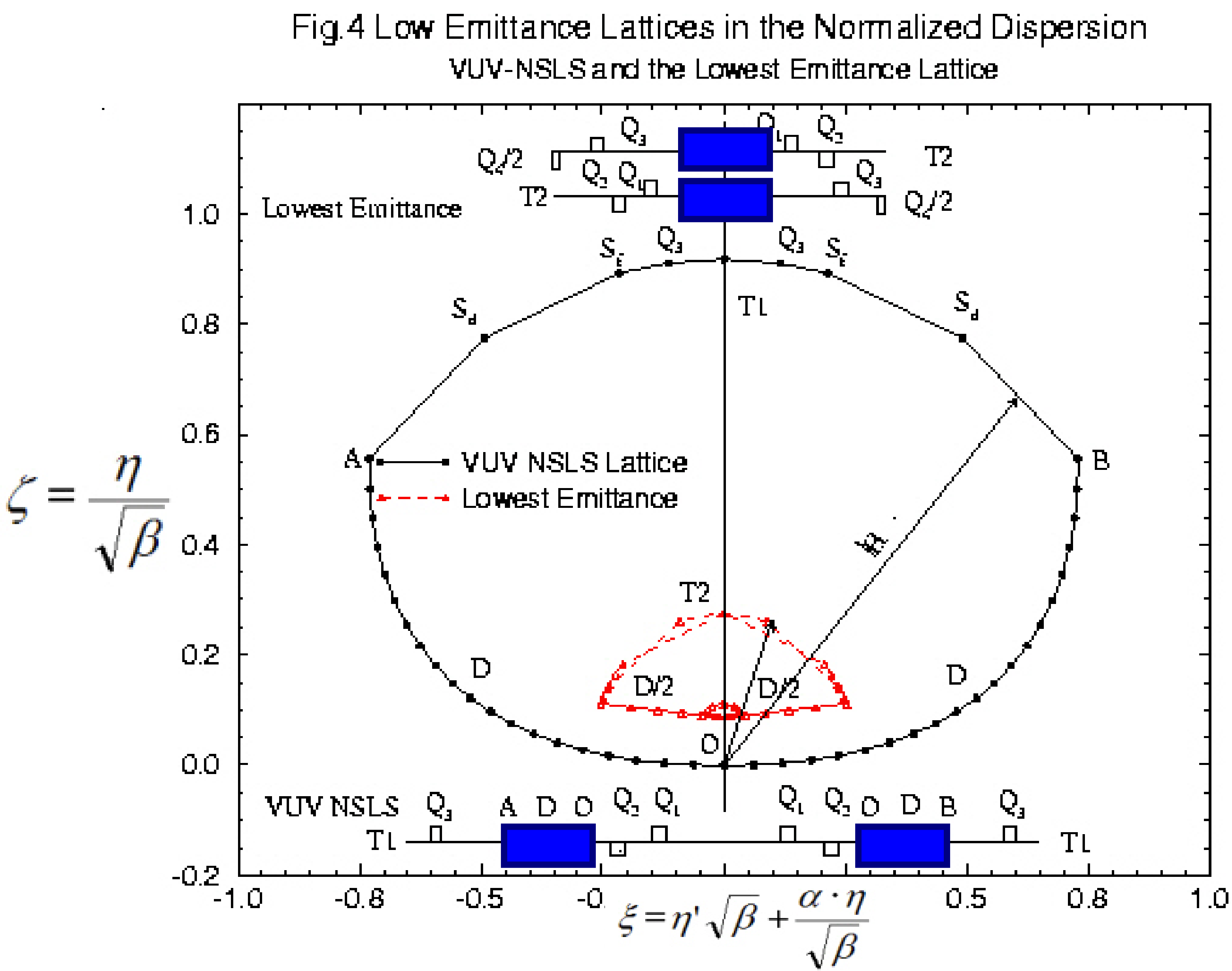
- The minimum emittance lattice requires reduction of the function H:
  - The normalized dispersion amplitude corresponds to the <H>$^{1/2}$
  - Conditions are for the minimum of the betatron function β_x and dispersion function D_x to have small values at the middle of the dipole (combined function dipole makes it even smaller).



$$\beta_{min} = Ld/2\sqrt{15}$$

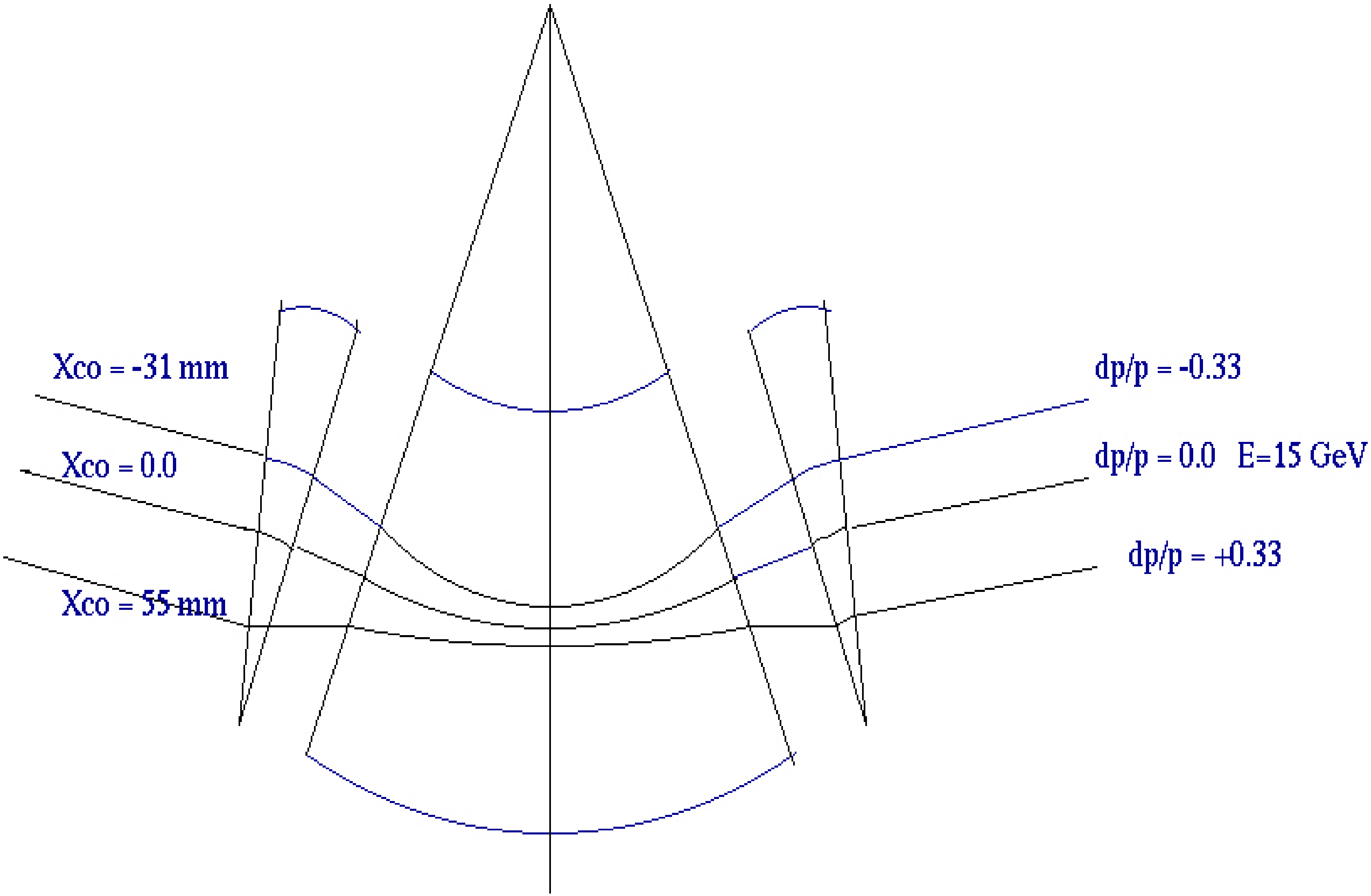
$$D_{xmin} = \theta * Ld/24$$

NSLS reduction of the emittance: 10 times

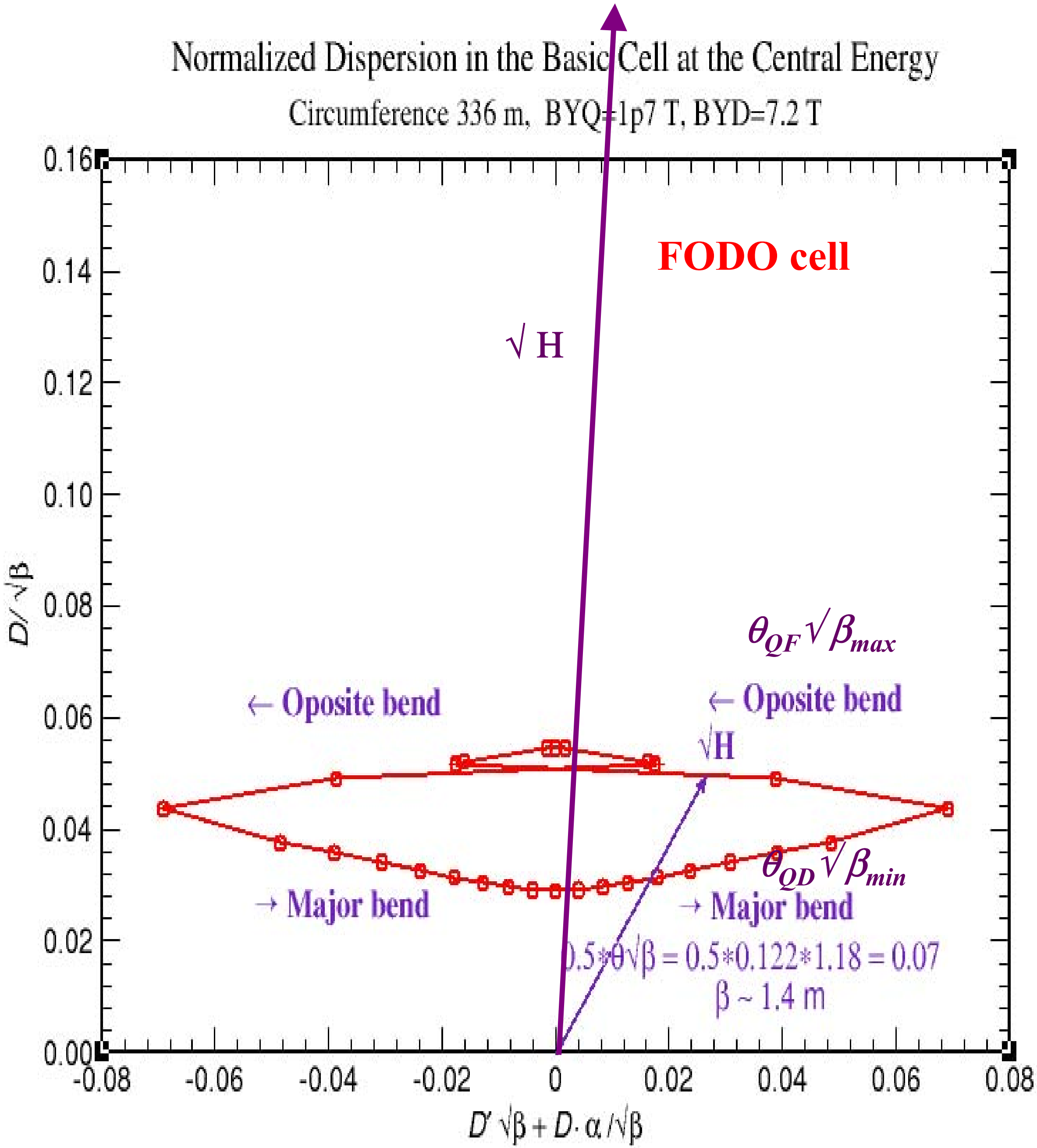


Non Scaling Minimum Emittance FFAG

D. Trbojevic

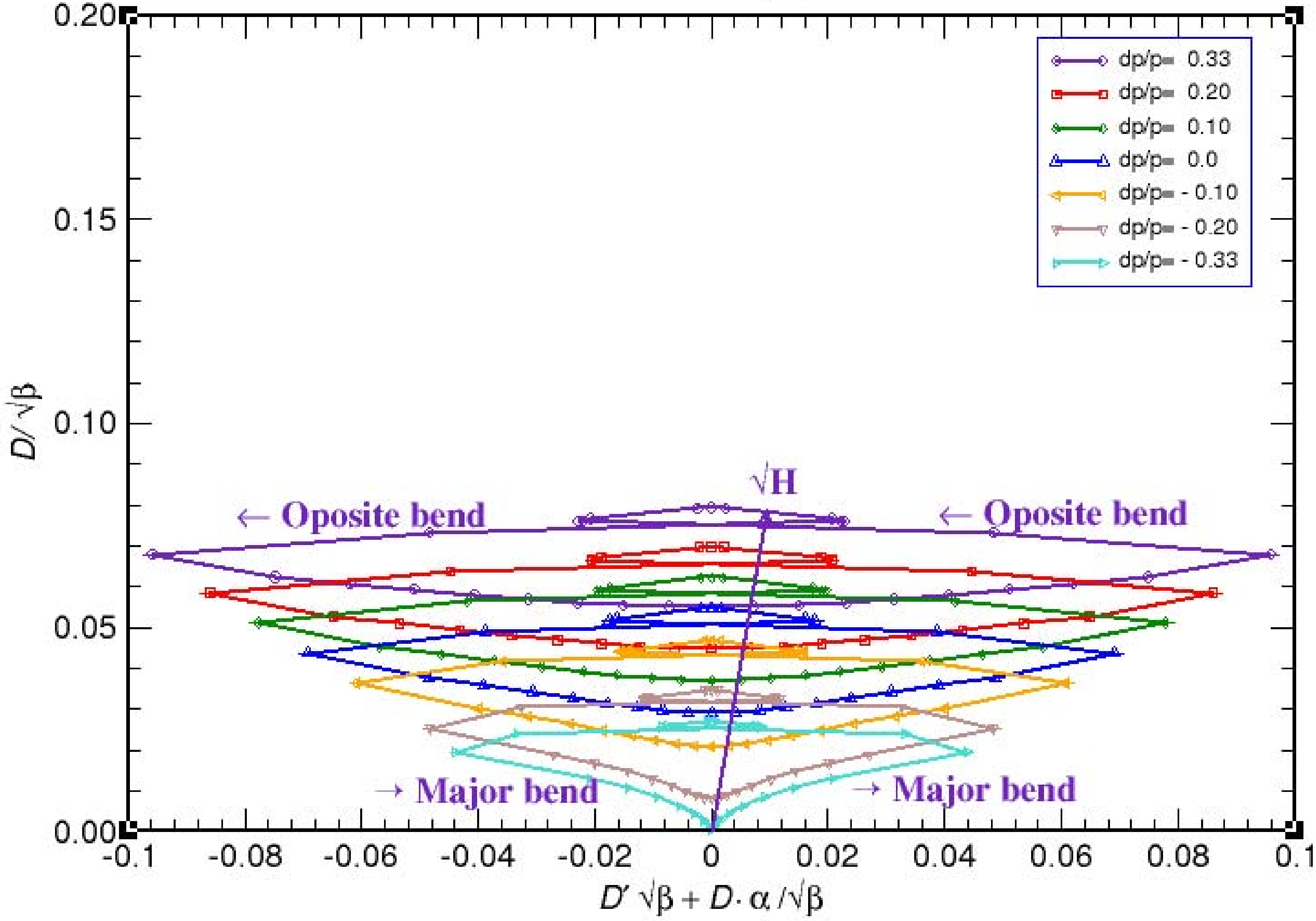


Dejan Trbojevic: Minimization of the H function applied for the FFAG design



Normalized Dispersion in the Basic Cell During Acceleration

Circumference 336 m, BYQ=1p7 T, BYD=7.2 T



Scaling or non- scaling FFAG?

Scaling FFAG properties:

- ❑ Zero chromaticity.
- ❑ Orbits parallel for different energies.
- ❑ Large momentum acceptance.
- ❑ Relatively large circumference (θ_1/θ_2).
- ❑ Relatively large physical aperture.
- ❑ RF:large aperture-follows the energy.
- ❑ Tunes are fixed for all energies.
- ❑ Negative momentum compaction.
- ❑ Orbits of the high energy particles are at high field, low energy particles at low field.

Non-Scaling (linear) FFAG properties:

- ❑ Chromaticity is changing.
- ❑ Orbits are not parallel.
- ❑ Large momentum acceptance.
- ❑ Relatively small circumference.
- ❑ Relatively small physical aperture.
- ❑ RF:small aperture-at the crest.
- ❑ Tunes move 0.4-0.1 in basic cell.
- ❑ Momentum compaction changes.
- ❑ Orbits of the high energy particles are at high field, low energy particles at low field.

FODO or TRIPLET or DOUBLET?

- ❑ For the same magnet properties larger circumference and larger X_{co}.
- ❑ For the same dispersion [$\Delta x = D_x * dp/p$] and the same magnet smaller field and larger circumference.
- ❑ The FODO has larger available free space.

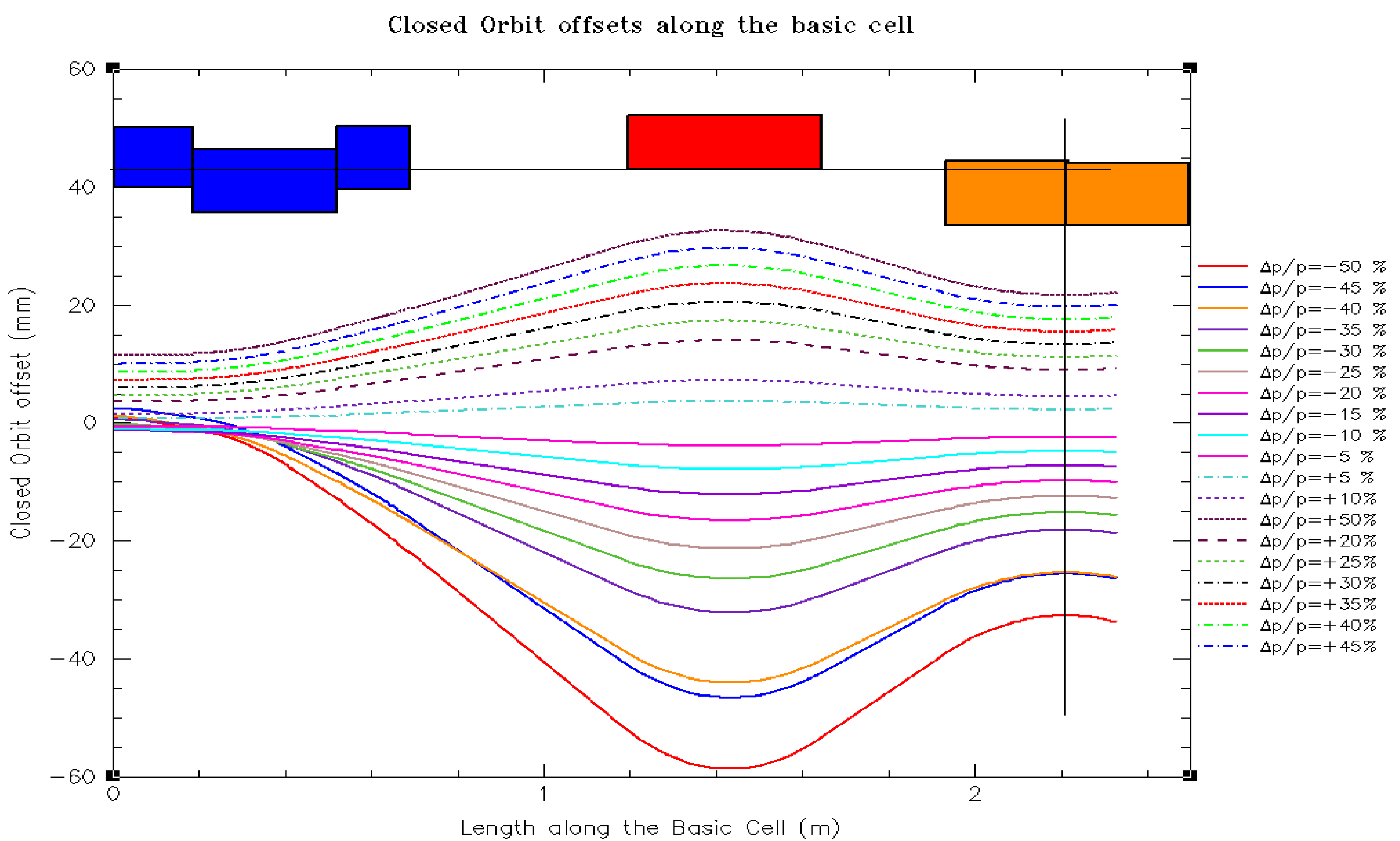
Recent FFAG workshops around the world

- http://hadron.kek.jp/FFAG/ KEK FFAG Synchrotron Home
- http://hadron.kek.jp/jhf/ffag99.html KEK FFAG 1999 Workshop
- http://hadron.kek.jp/jhf/ffag2000.html KEK FFAG 2000 Workshop
- http://hadron.kek.jp/FFAG/FFAG02_HP/top.html KEK FFAG 2002 Workshop
- http://hadron.kek.jp/FFAG/FFAG03_HP/top.html KEK FFAG 2003 Workshop
- http://nfwg.home.cern.ch/nfwg/nufactwg/FFAG/FFAGAgenda2.html CERN FFAG 2000
- http://sitka.triumf.ca/doug/prism_workshop/ FFAG Muon Source 2000 (TRIUMF)
- http://www.cap.bnl.gov/mumu/conf/ffag-021028/ LBNL FFAG 2002 Workshop
- http://www.cap.bnl.gov/mumu/conf/ffag-031013/ BNL FFAG 2003 Workshop
- KEK FFAG 2004 Workshop - October 13th-16th
- Cyclotrons 2004, October 18-22, Tokyo, Japan, will have an FFAG session

Progress in our BNL FFAG lattice design:

- 1999-2001 - Dynamical aperture was reduced due to sextupoles.
- October 2002: the small opposite bend was introduced:
  - This change allowed removal of the sextupoles.
  - Very large dynamical aperture.
  - The tunes are still vary-but between 0.4-0.1 in the basic cell.
- January 2003: Additional defocusing quadrupole was removed and a larger area for the cavity placement was provided.
  - The lattice became extremely simple and easy to analyze.
  - The analytical solutions showed problems with the available codes.
- May 2003: Both magnets are complete combined function magnets.
- The acceleration might require either additional harmonic or reduction of the path length difference.
- The magnets required are being investigated by the magnet division at Brookhaven National Laboratory. It looks like there are simple solutions.
- 2003-2004 Analytical and different codes results and tracking work(PTC, COSY, MADX-PTC, SYNCH etc.) have shown no stoppers.

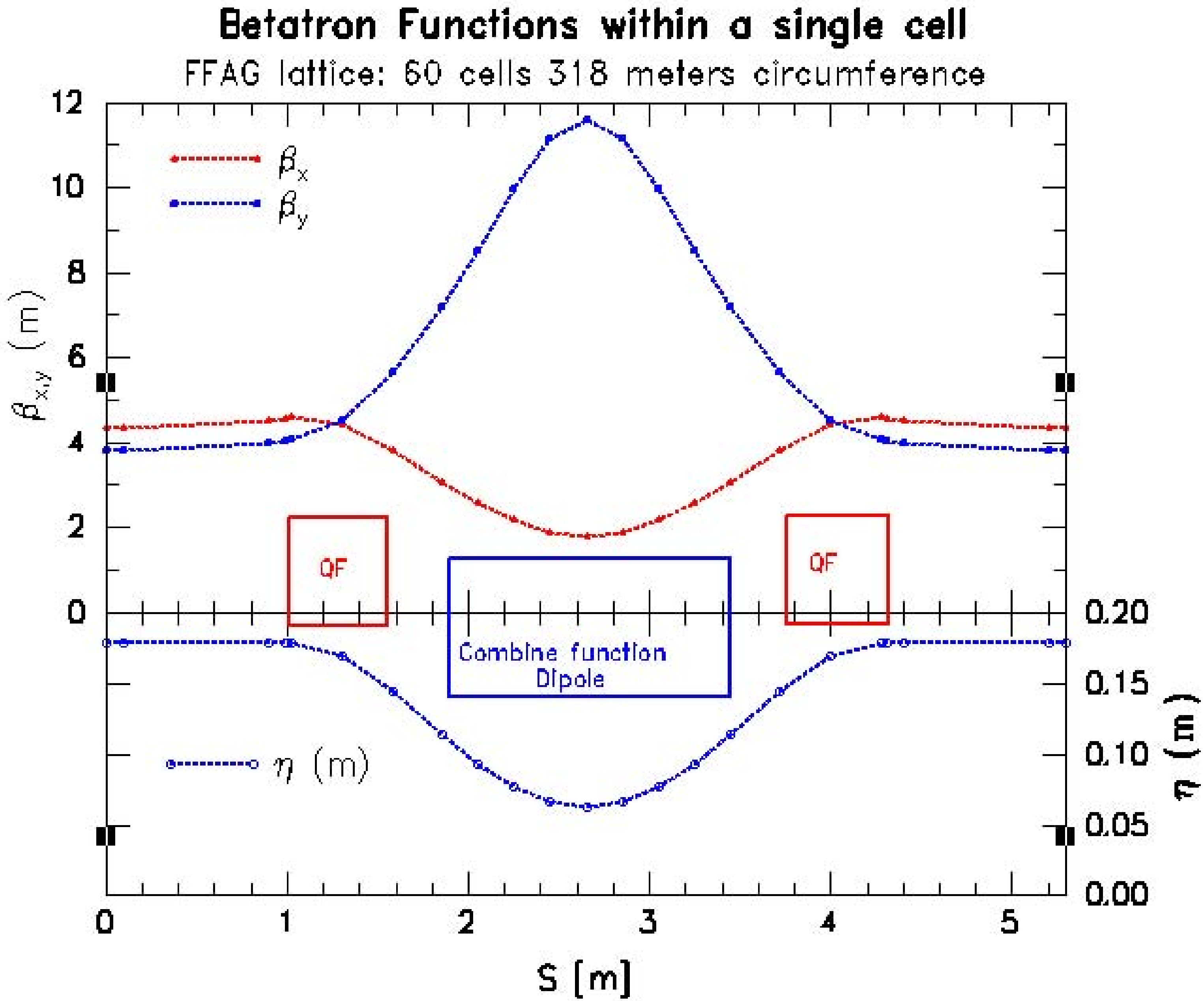
FFAG solution presented in the talk December 2000.



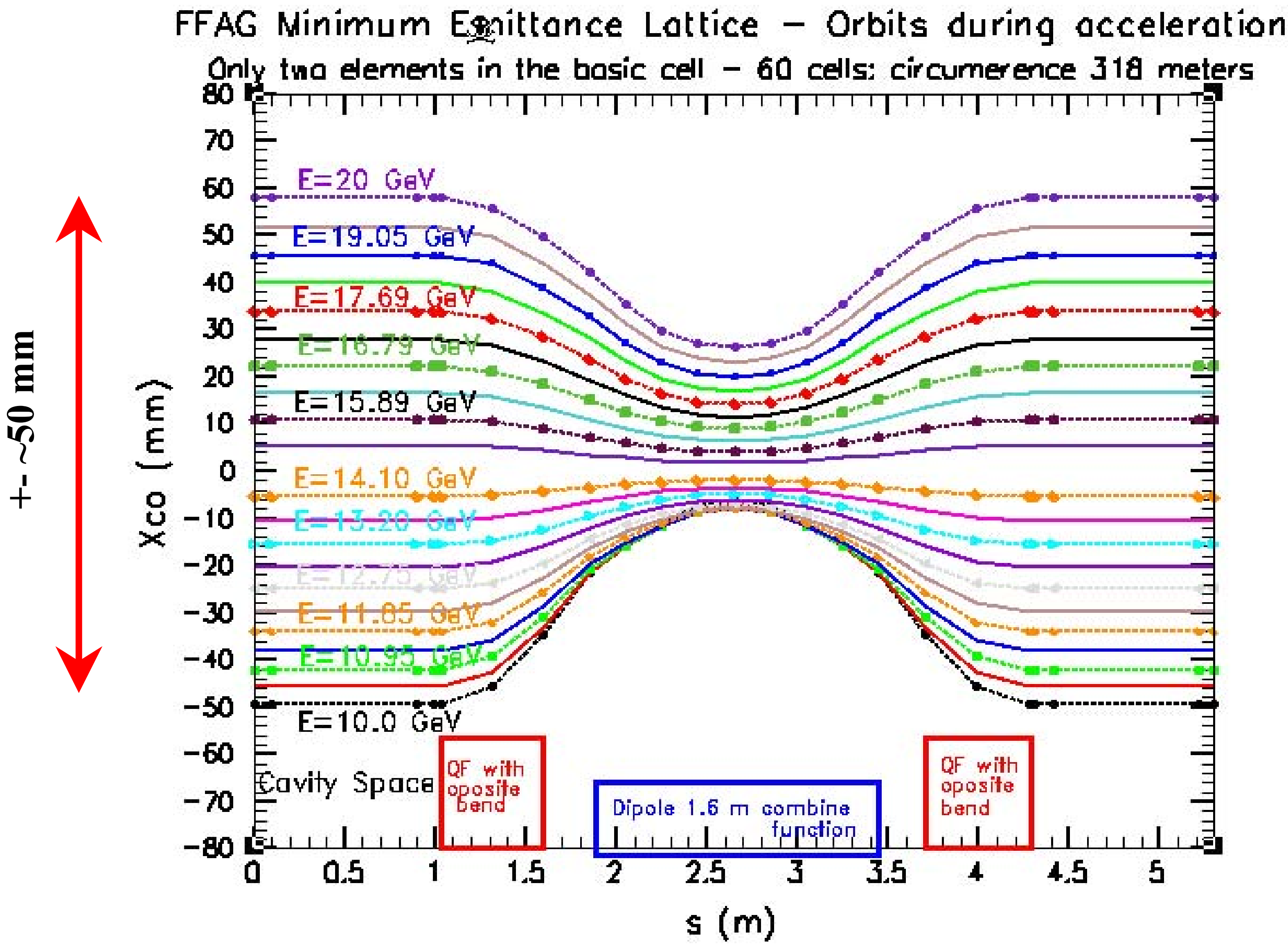
Back to the plan of presentation: Examples

- **Muon acceleration example 10-20 GeV**
- **Proton Driver 200 MeV-1.2 GeV**
- **eRHIC – electron acceleration from 3 GeV to 10 Gev**
- **Electron Demonstration Ring: acceleration from 10 MeV to 20 MeV, Circumference=15 m**

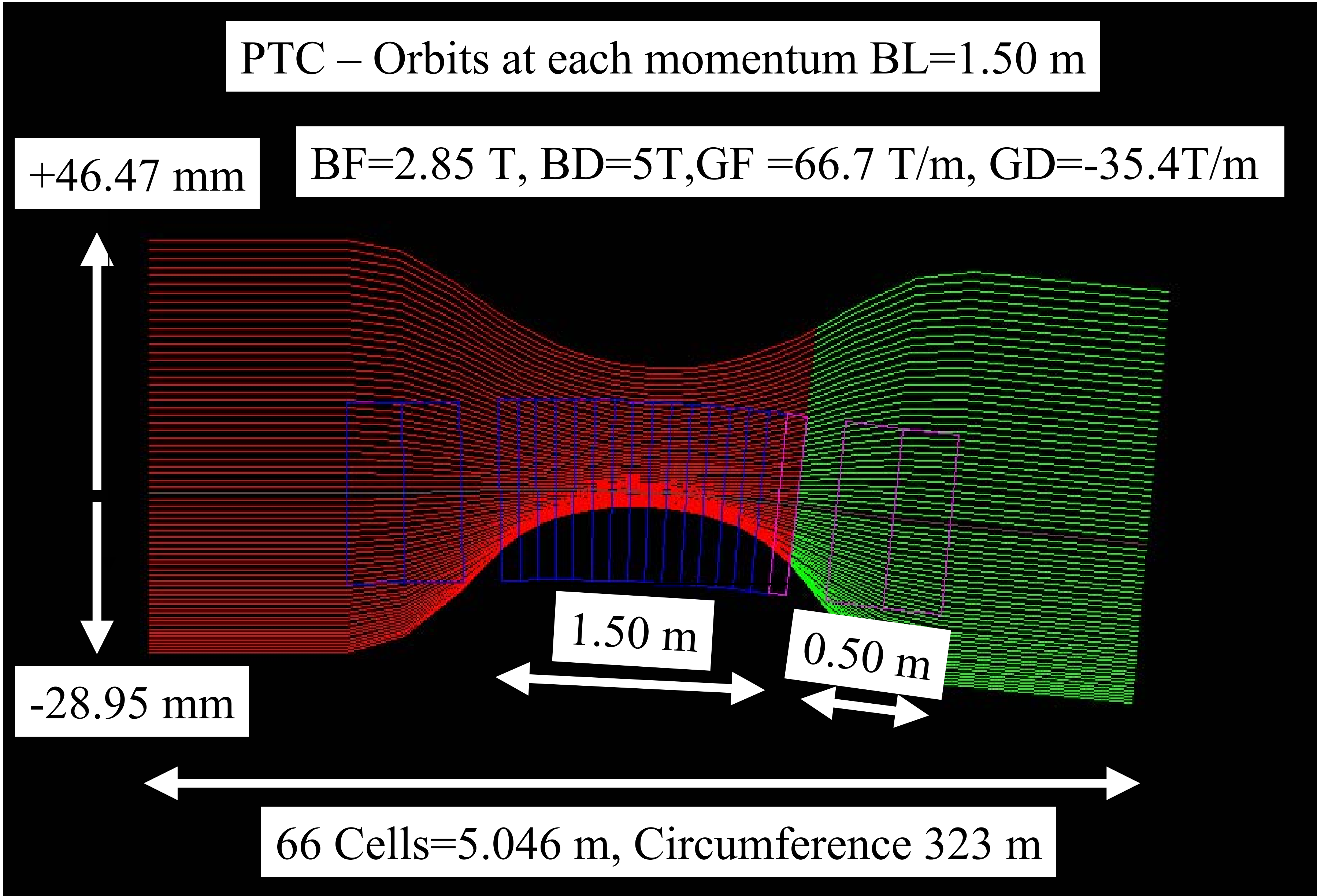
Dejan Trbojevic: Muon Acceleration 10-20 GeV



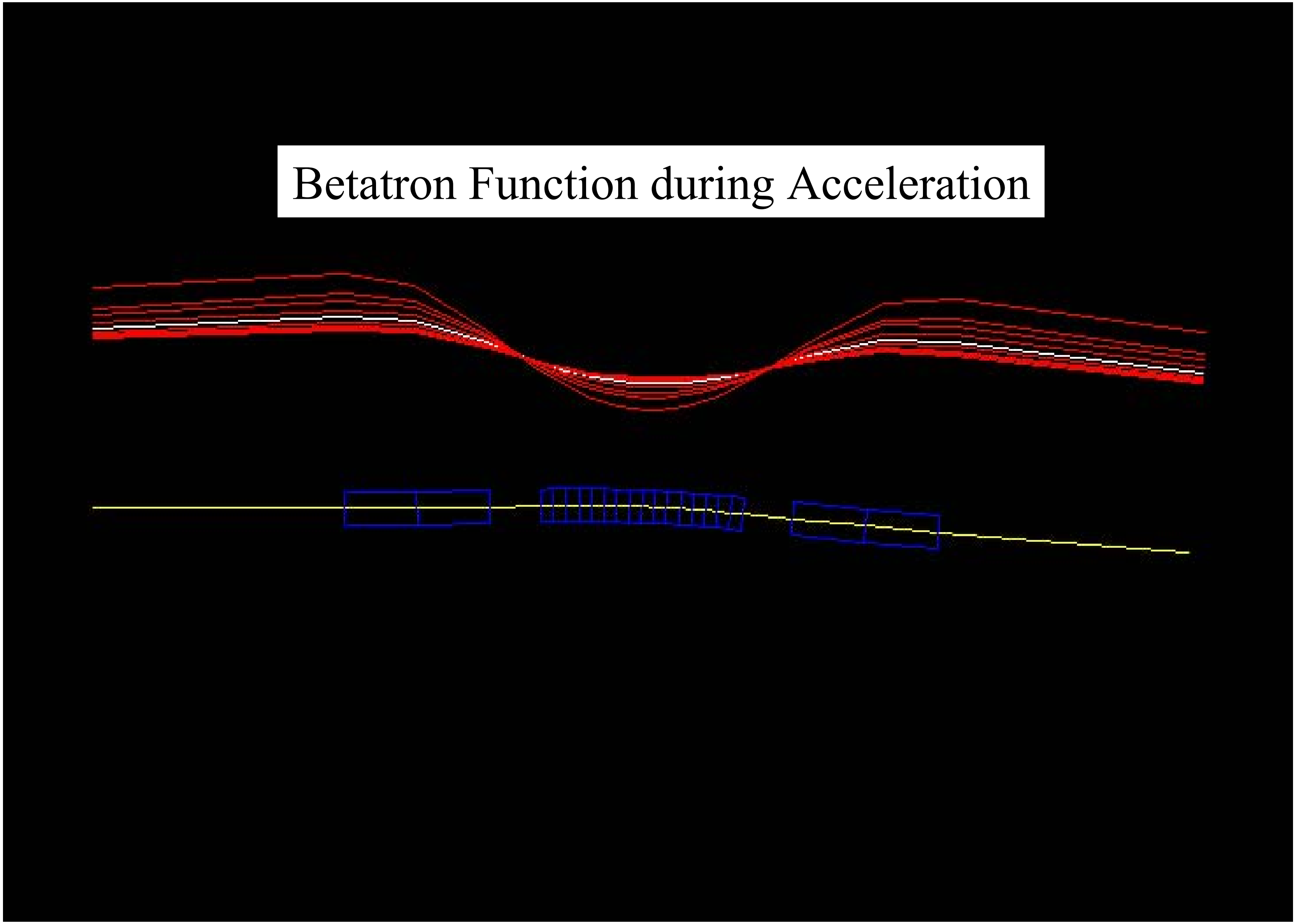
Dejan Trbojevic: Muon Acceleration 10-20 GeV



Dejan Trbojevic: Muon Acceleration 10-20 GeV



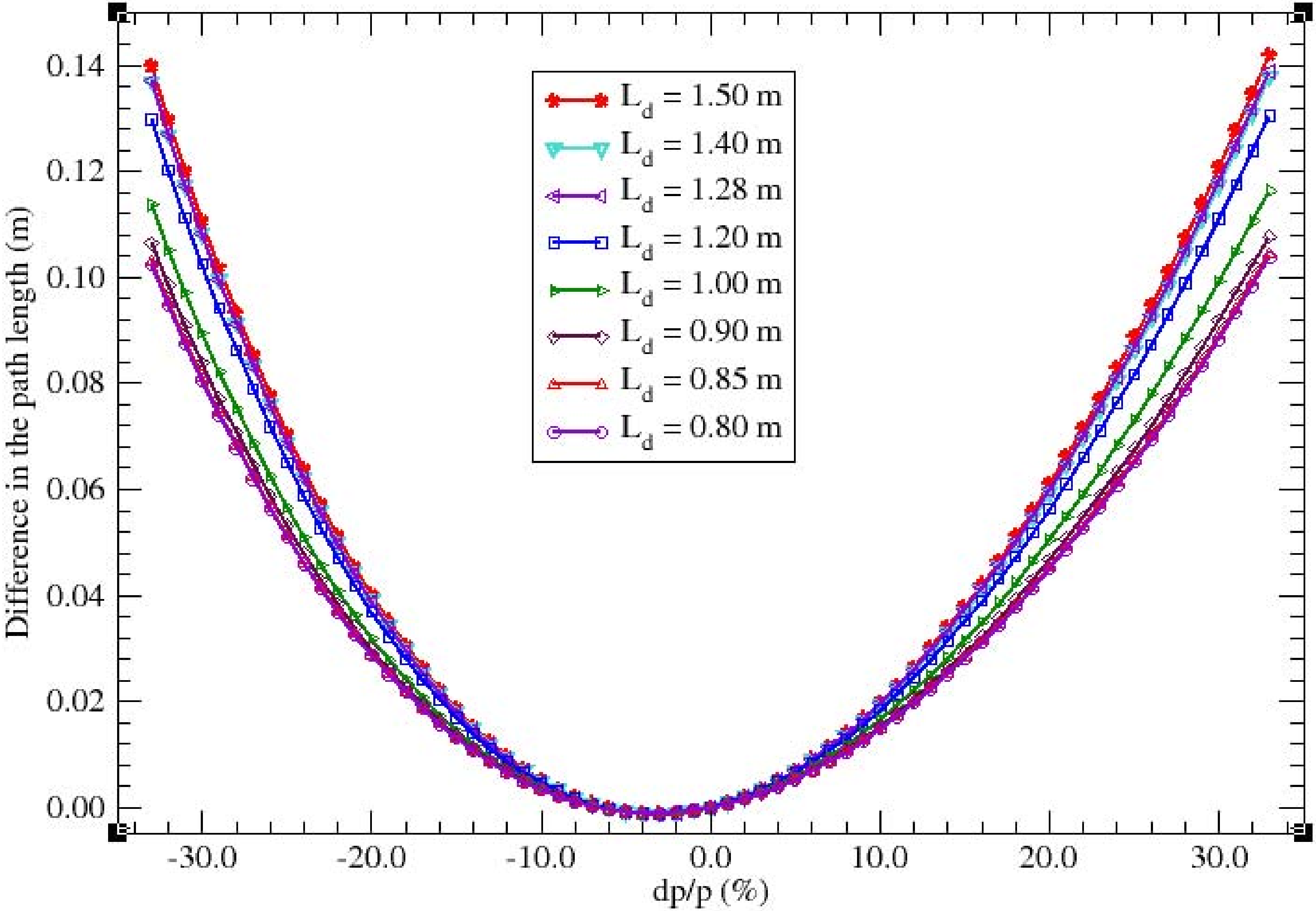
Dejan Trbojevic: Muon Acceleration 10-20 GeV



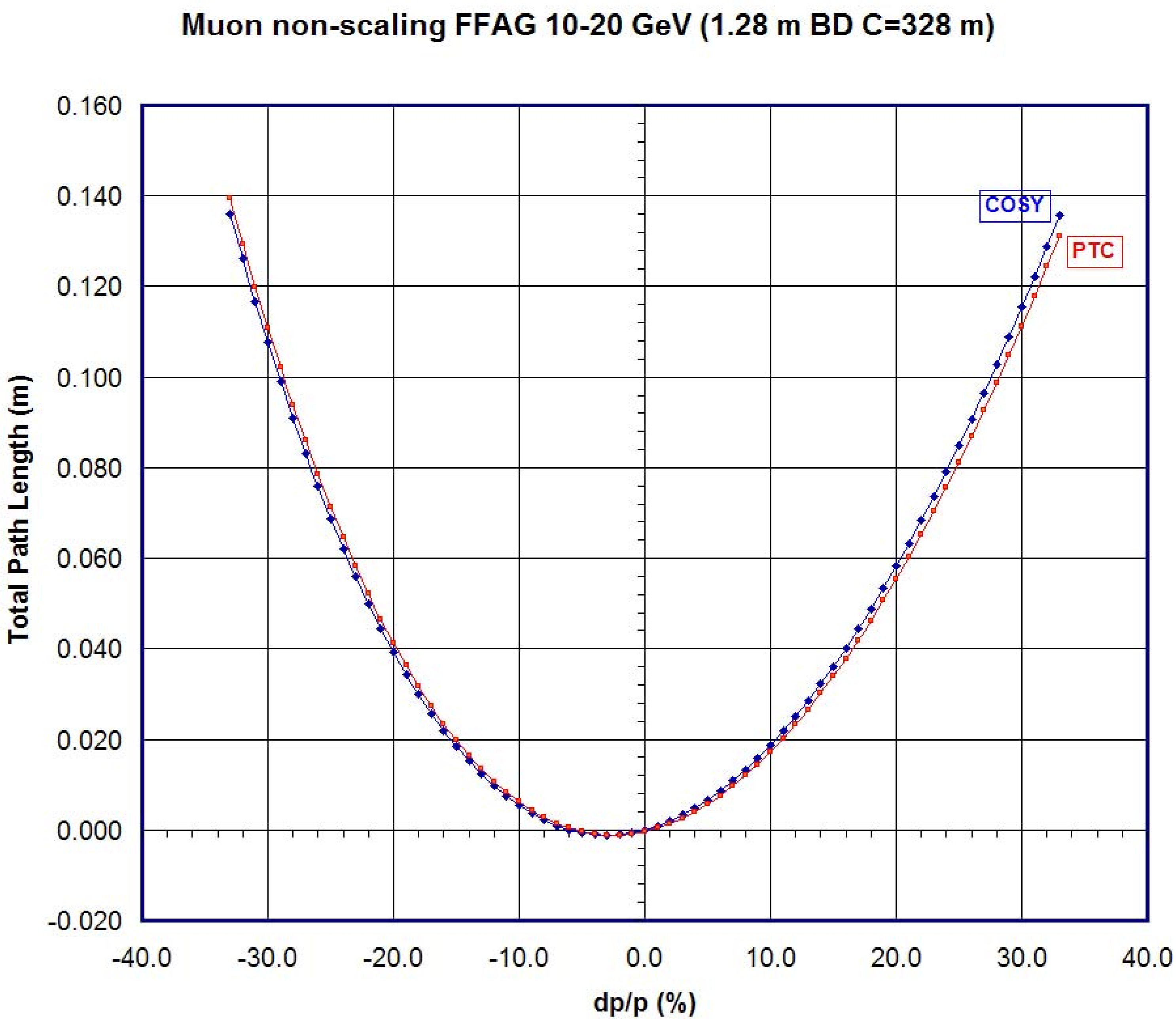
Dejan Trbojevic: Muon Acceleration 10-20 GeV

The Non-scaling FFAG lattices fixed circumferences: C_o=328 m

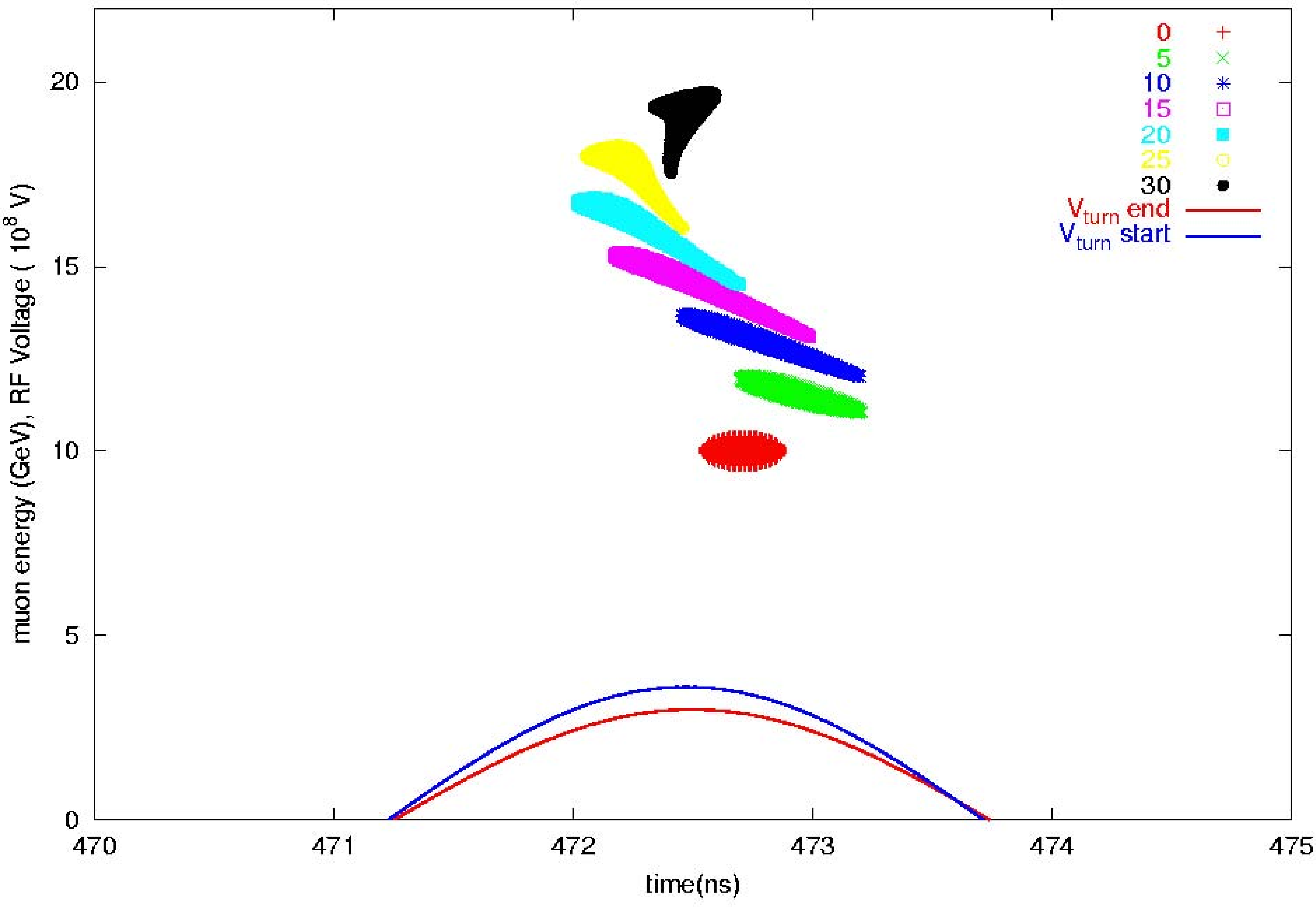
The path length difference of the corresponding lattice - range of the main bend lengths: 0.8 m - 1.5 m



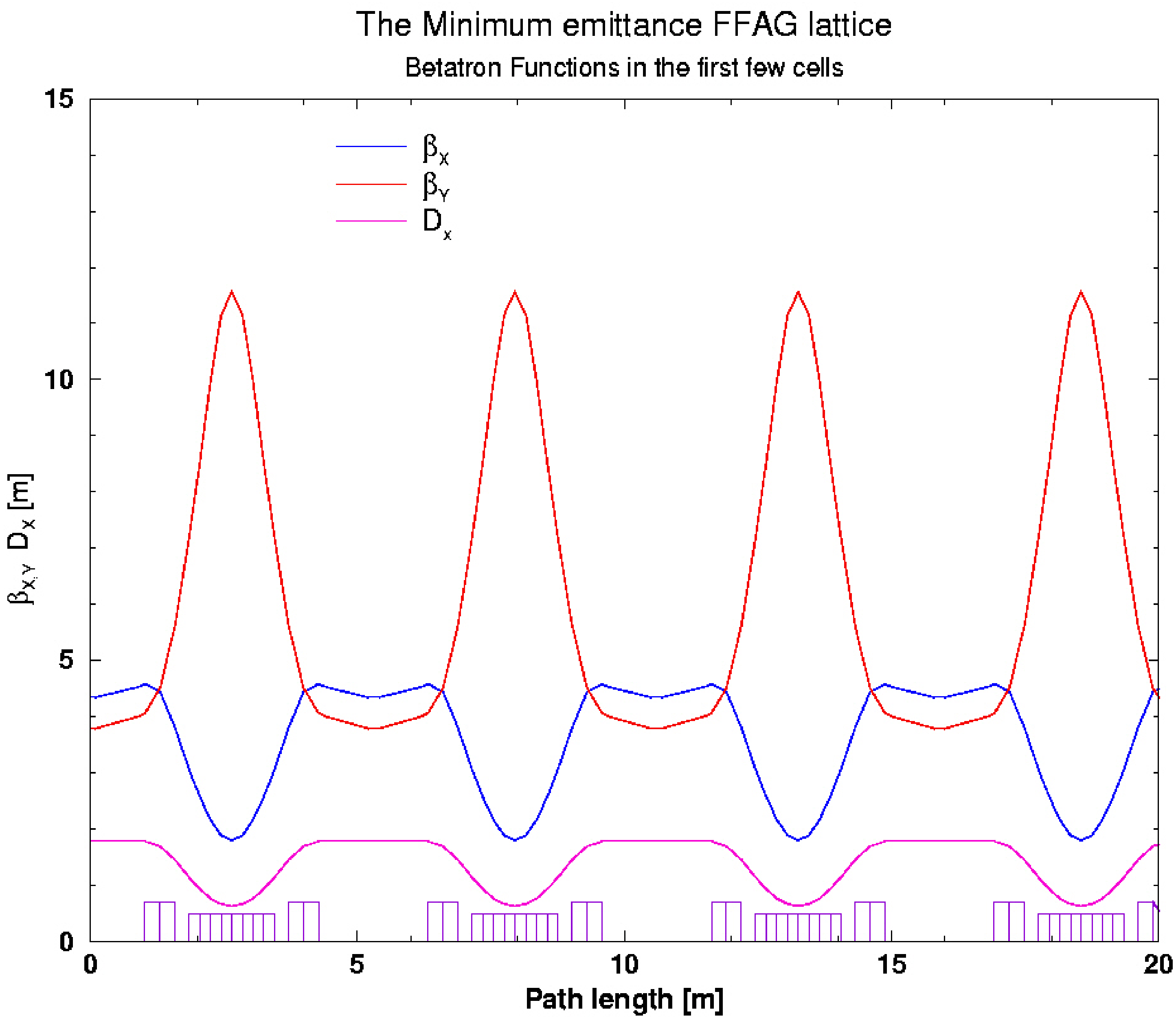
D. Trbojevic: Muon acceleration10-20 GeV



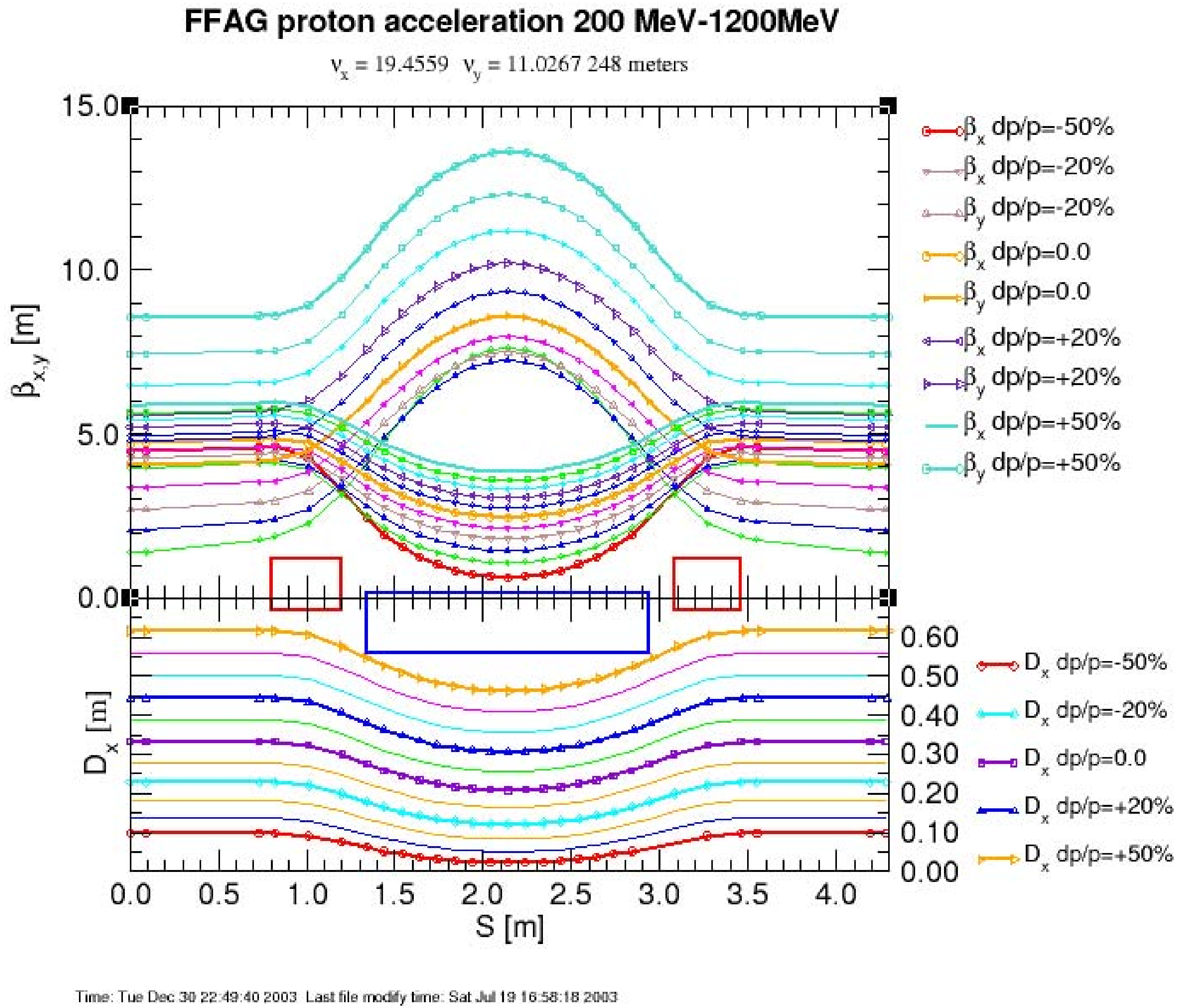
Mike Blaskiewicz: Muon Acceleration 10-20 GeV



Dejan Trbojevic: Muon Acceleration 10-20 GeV

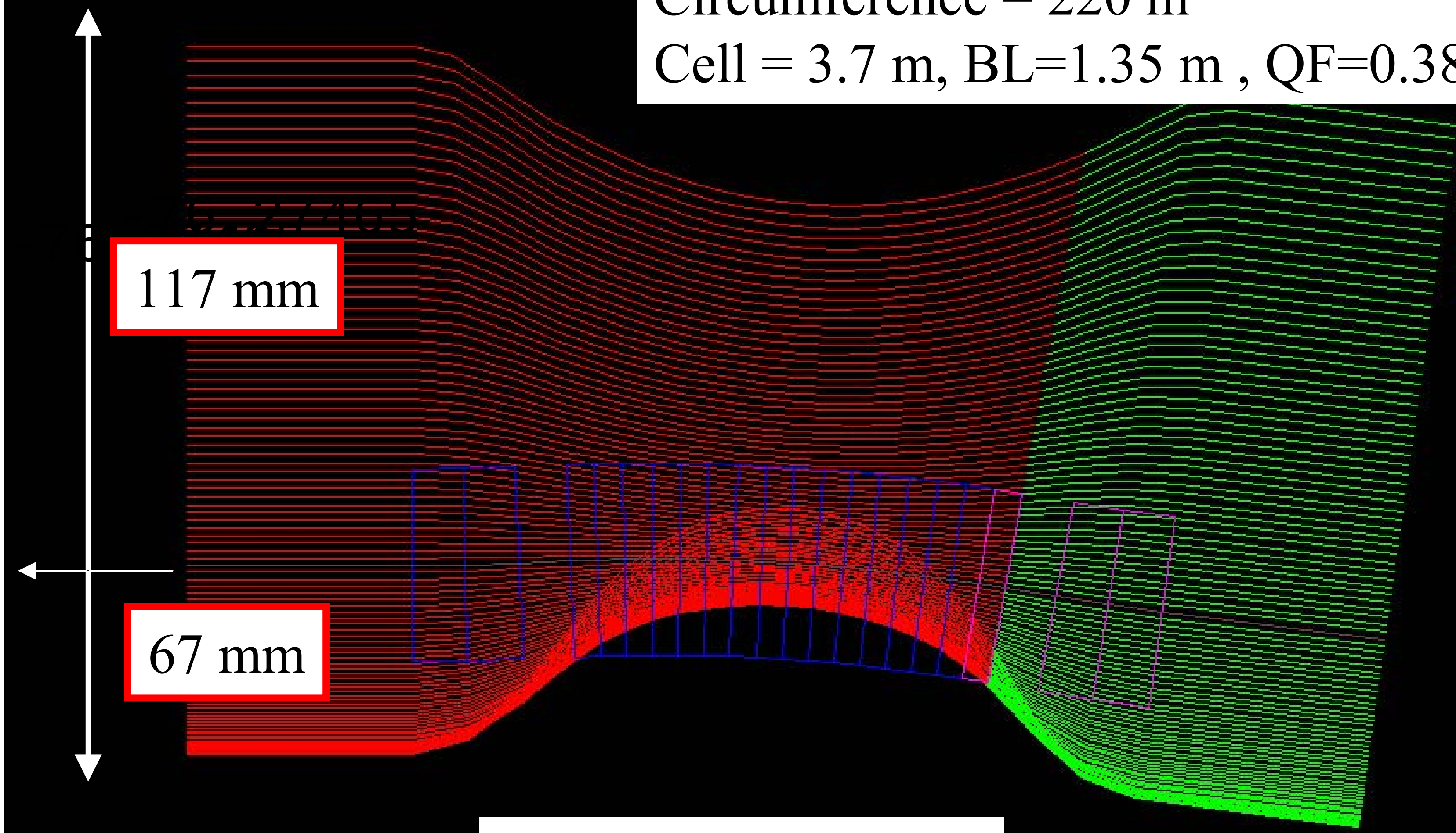


FFAG Proton Driver



FFAG Proton Driver

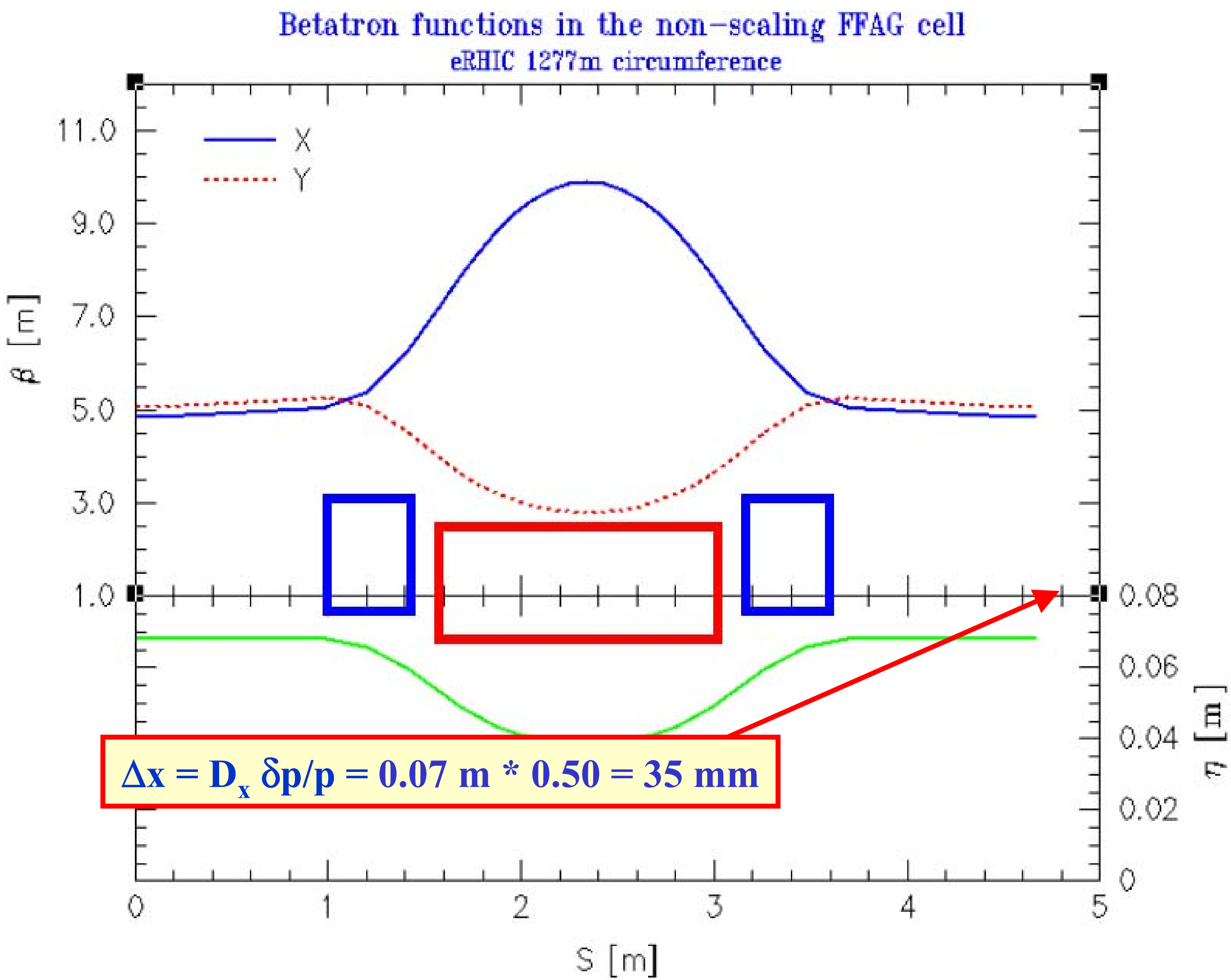
Circumference = 220 m
Cell = 3.7 m, BL=1.35 m , QF=0.38m



dp/p = -52 % - +52 %

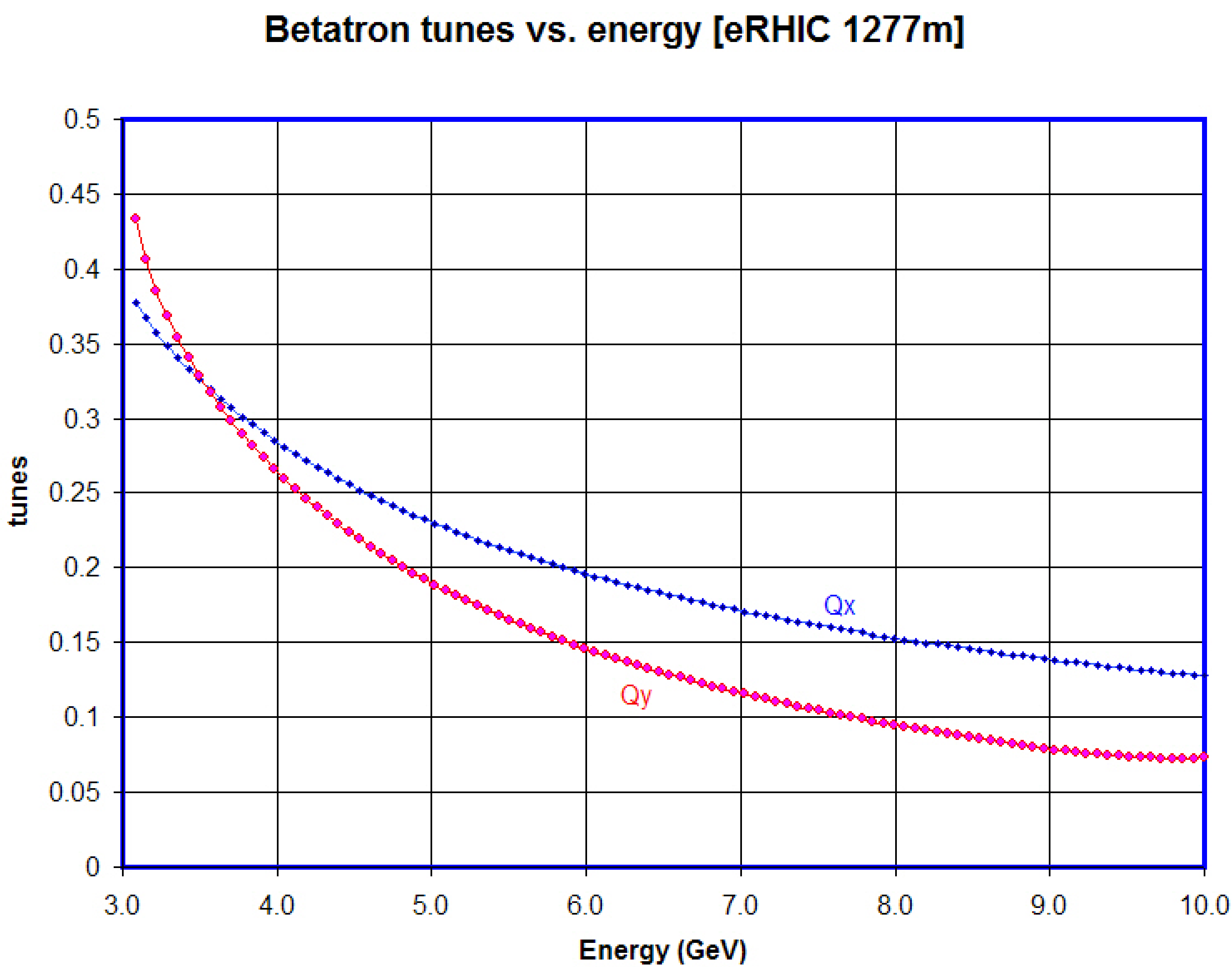
Bo=0.5858 T, Bneg=-0.42 T, GradientF=6.1T, GradientD=-3.1T

eRHIC: Electron acceleration from 3-10 GeV with a non-scaling linear field FFAG lattice

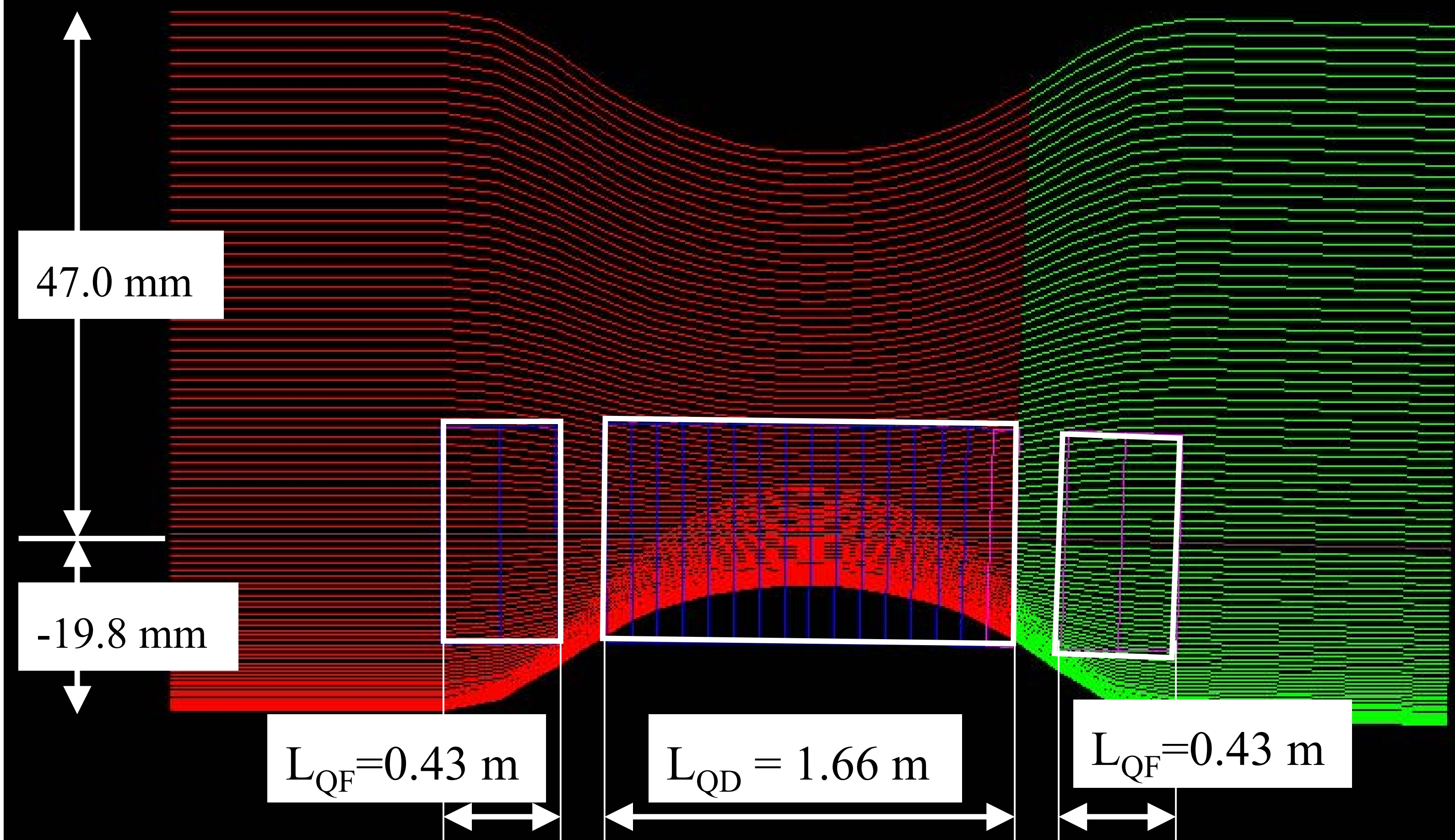


$\Delta x = D_x\ \delta p/p = 0.07$ m * 0.50 = 35 mm

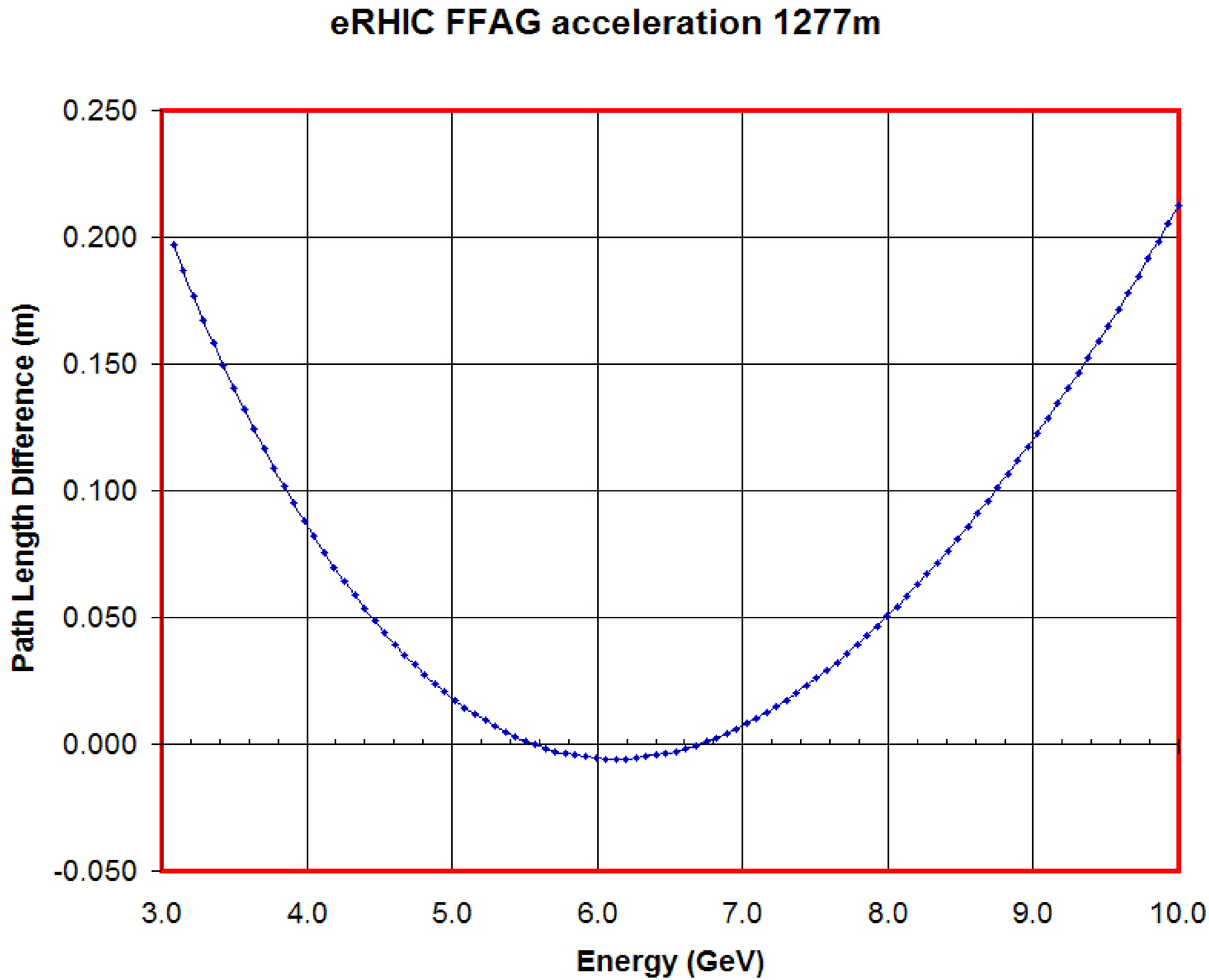
eRHIC: Electron acceleration from 3-10 GeV with a non-scaling linear field FFAG lattice



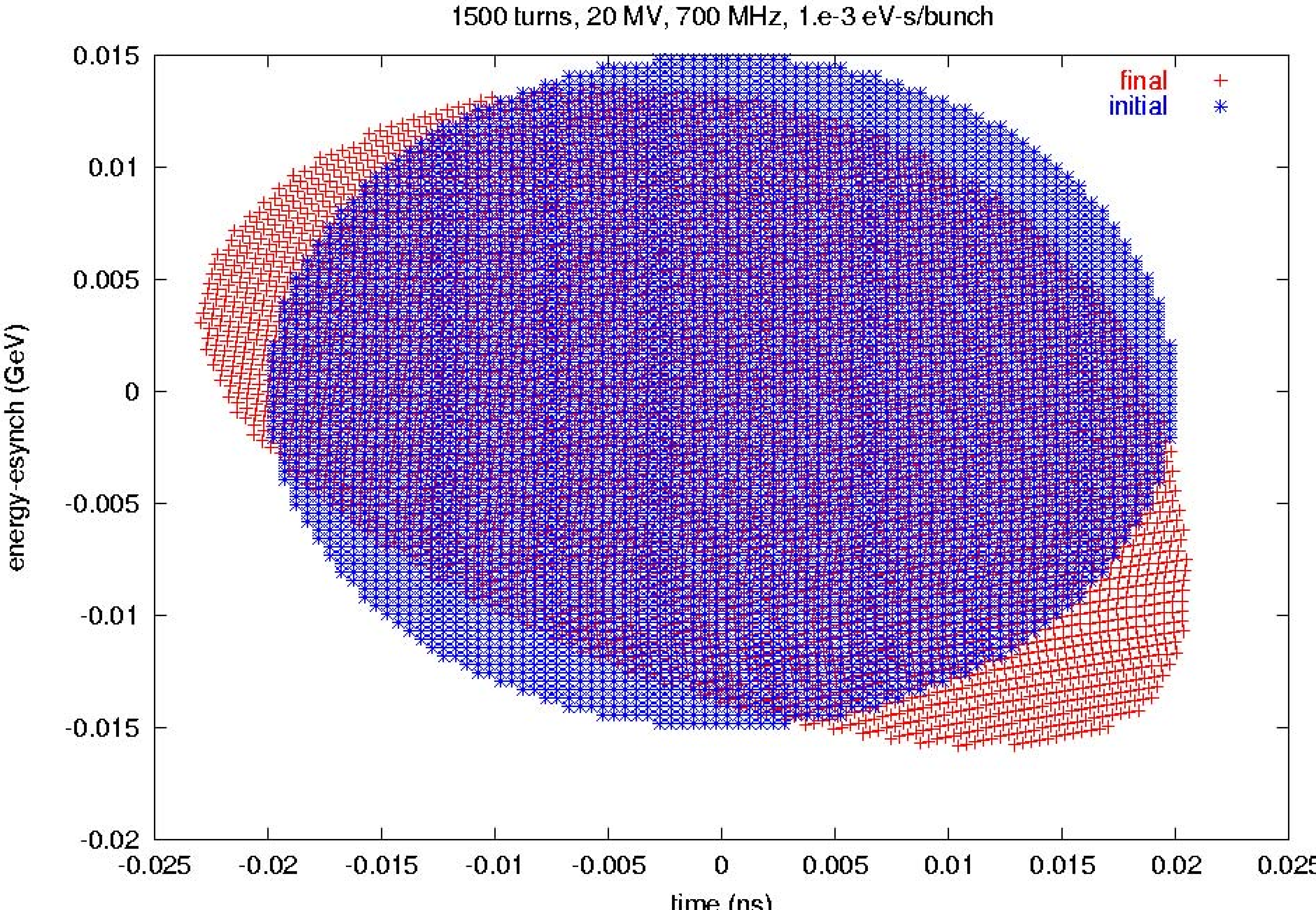
Electron path during acceleration within the basic cell
C=1277 m, 273 cells, L=4.68 m



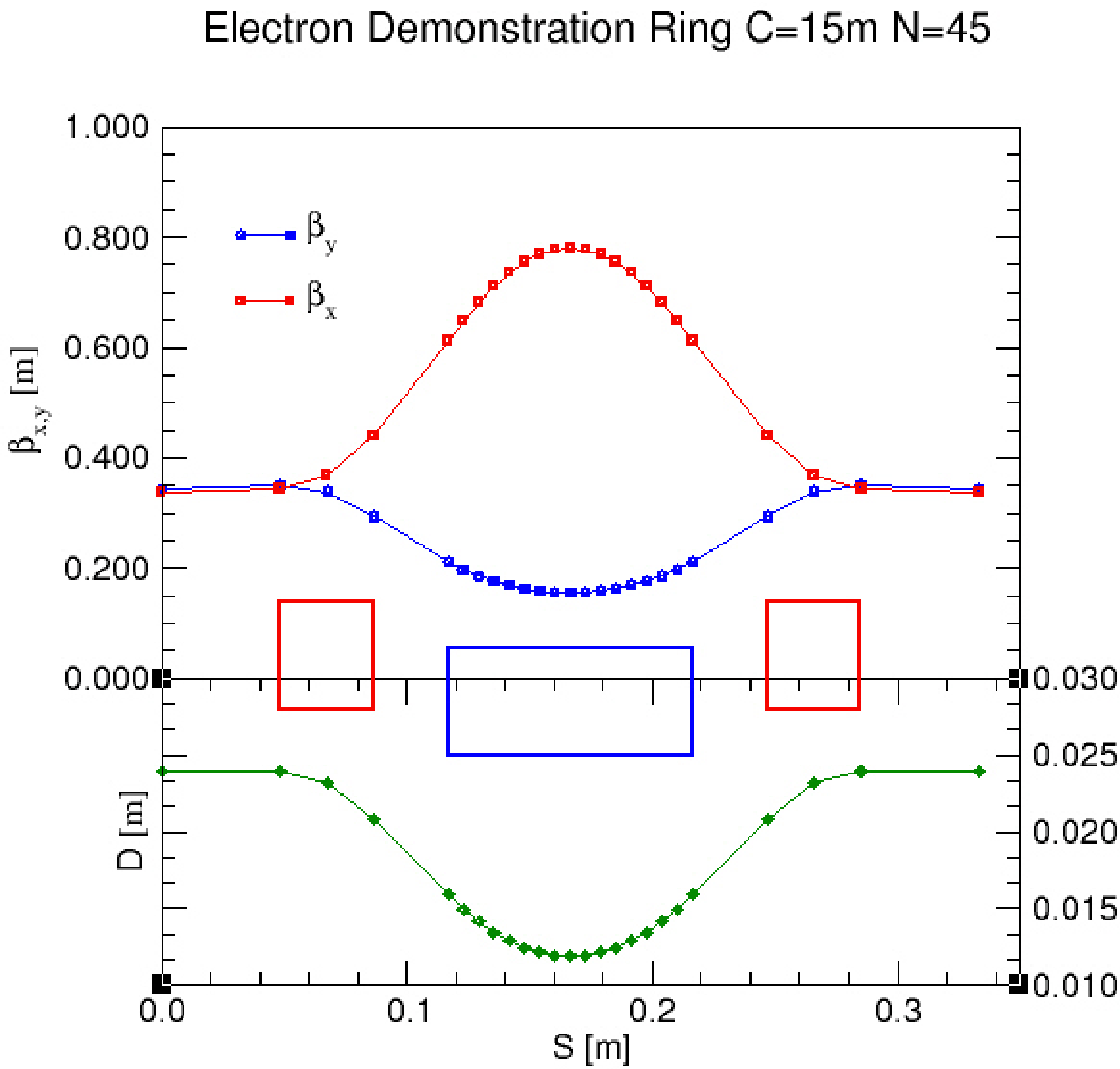
eRHIC: Electron acceleration from 3-10 GeV with a non-scaling linear field FFAG lattice



Mike Blaskiewicz eRHIC: Electron acceleration from 3-10 GeV



D. Trbojevic: Electron demonstration ring 10-20 MeV



D. Trbojevic: Electron demonstration ring 10-20 MeV

Dimensions and Fields:

GRADIENTS: $GF = 7.06035$ T/m

$GD = -4.59590$ T/m

Dimensions:

$L_{BD} = 10$ cm

$L_{QF} = 3.8$ cm

CAV = 10.6 cm

Drift = 3.12 cm

Bending Fields:

$By_{QD} = 0.1093$ T

$By_{QF} = -0.0520$ T

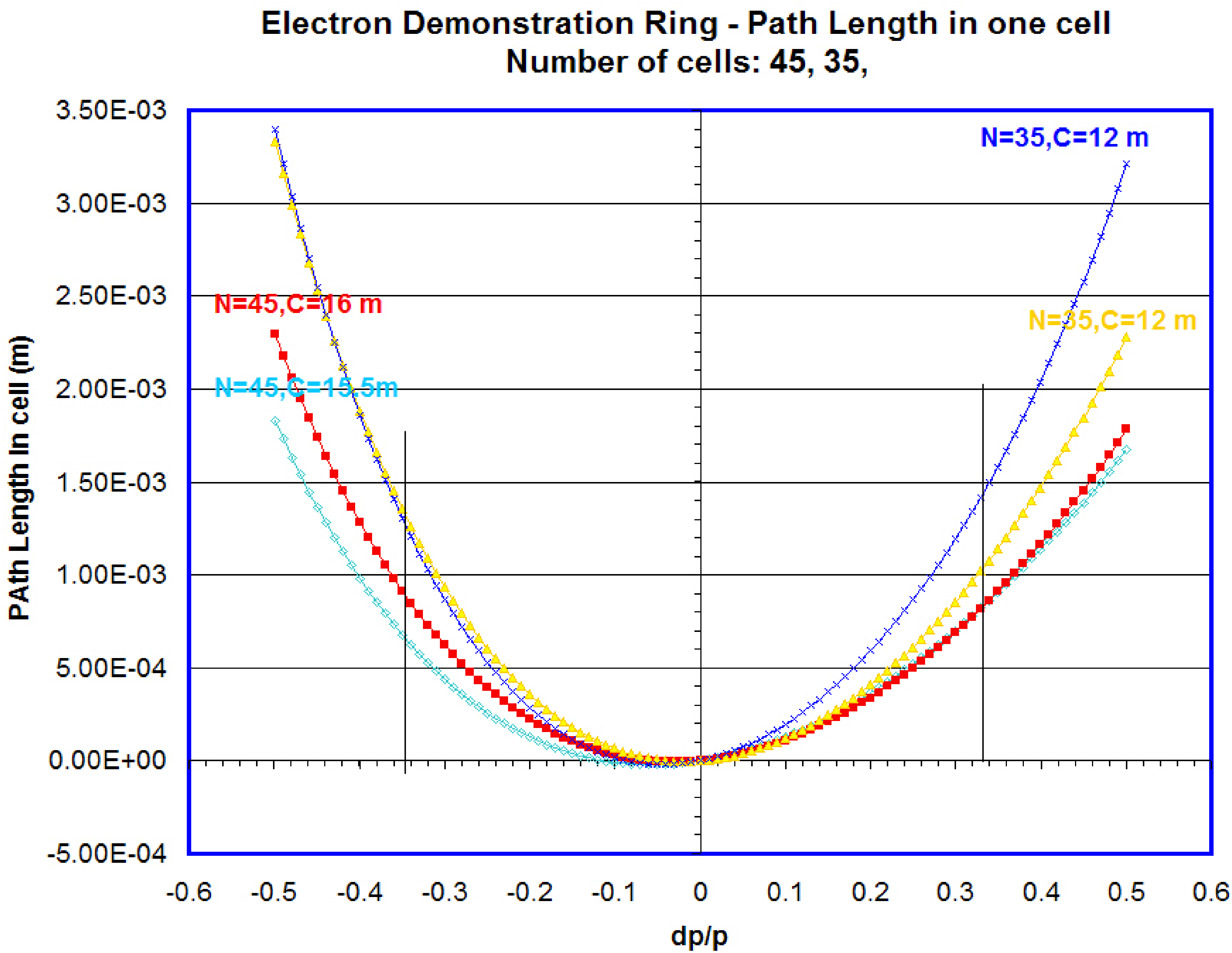
Bending angles:

$ANG_{QD} = 0.2186575$

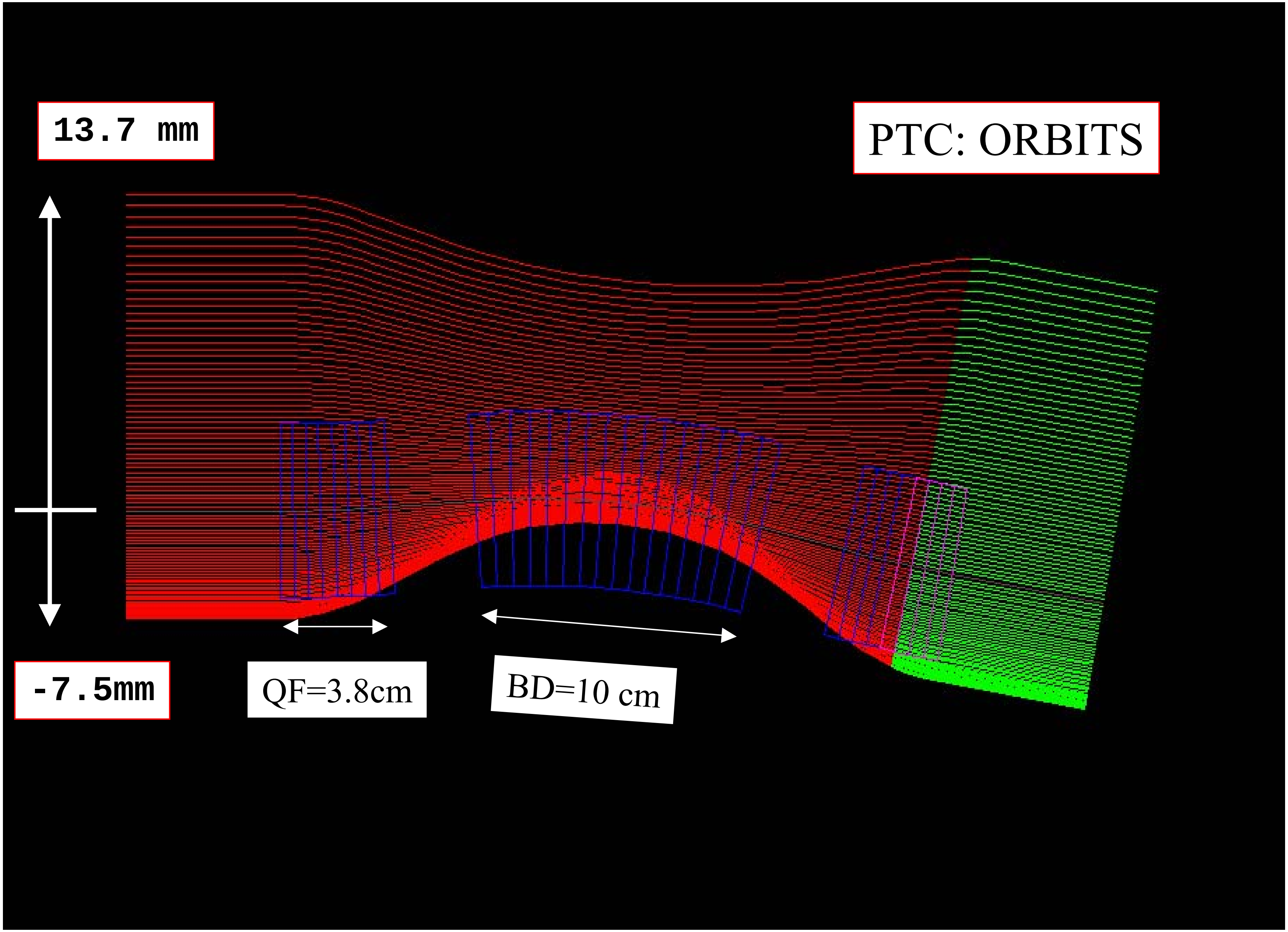
$ANG_{QF} = -0.039516$

$\theta_2/\theta_1 = 0.180$

D. Trbojevic: Electron demonstration rings 10-20 MeV



D. Trbojevic: Electron demonstration ring 10-20 MeV



FFAG's within the BNL?

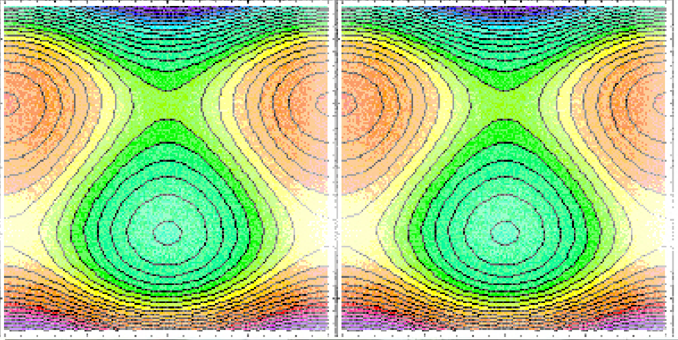
Team of experts at BNL has been formed: R. Palmer, E. D. Courant, J. Kewisch, S. Ruggiero, M. Blaskiewicz, S. Berg, S. Kahn, R. Fernow, N. Tsoupas, D. Trbojevic …

Where?

- Electron demonstration ring 10-20 MeV? (ATF or el. cooling).
- Proton (heavy ion) driver: for the 'Super-beam' or muon acceleration for the neutrino factory?
- Instead of CYCLOTRON for the isotope production?
- NSLS upgrade?
- eRHIC?
- Proton or carbon therapy?
- Proton driven nuclear reactor?

FFAG04 at TRIUMF : A great personal satisfaction after a long but persistent struggle:

- The first publication was from the Montauk workshop on **September 30, 1999**: Trbojevic, D., Courant, E. D., and Garren, A., **FFAG Lattice Without Opposite Bends**,
- Trbojevic, D., "**FFAG lattice without opposite bends",** KEK Workshop on FFAG Synchrotrons, **October 11, 2000**.
- Accelerator physics seminar talk at Brookhaven National Laboratory: Dejan Trbojevic, **December 14, 2000**: **"Fixed Field Alternating Gradient Lattice (FFAG) without Opposite Bends".**
- Muon Collaboration Meeting at Berkeley, **February 2, 2001**. Dejan Trbojevic: "Some taught about re-circulator".
- **Collaboration Meeting Neutrino Factory at Brookhaven National Laboratory.**
- Trbojevic, D., Courant, E., Garren, A. **"Fixed field alternating gradient lattice design without opposite bends"**. Eighth European Particle Accelerator Conf. (EPAC'02), Paris, France, **June 3-7, 2002**, pgs. 1199-1202 (2002) BNL-69007.
- **PAC2003, Portland, Oregon, May 16, 2003, "FFAG LATTICE FOR MUON ACCELERATION WITH DISTRIBUTED RF",** D. Trbojevic, J.S. Berg, M.Blaskiewicz, E.D. Courant, R. Palmer, BNL, Upton, New York, A.A. Garren, LBL, Berkeley, California, USA.
- FFAG update at the KEK workshop July 8, 2003.
- FFAG workshop at BNL (October 2003)
- TRIUMF FFAG workshop (April 2004)



FFAG
2004
TRIUMF

FFAG Workshop, TRIUMF, Vancouver B.C., 15-21 April, 2004

FFAG 2004, Vancouver BC,
Workshop Agenda - Final programme

Auditorium

Wednesday 14 April		
1:25-1:30 pm	Introduction	S. Koscielniak
1:30-2:00 pm	Classical FFAGs	Yoshi Mori
2:00-3:00 pm	Physics potential of an FFAG such as PRISM, **Part 1**, **Part 2**, **Part 3**	Yoshitaka Kuno
3:00-3:15 pm	Break	
3:15-4:00 pm	FFAGs as part of neutrino factory & muon collider	Carol Johnstone
4:00-4:30 pm	Nonlinear longitudinal dynamics of non-scaling FFAG	**Shane Koscielniak**

ISAC2 Conference Room

Thursday 15 April		
8:30-9:00 am	**Registration**	
9:00-9:20 am	Welcome	TRIUMF director
9:20-09:50 am	Workshop organization......	
Designs of FFAG-based proton/muon/electron sources		
9:50-10:30 am	Resonance Crossing Studies at HIMAC	**Shinji Machida**
10:30-11:15 am	1.5GeV proton FFAG as injector to BNL AGS Field profile adjustment, harmonic number jump, etc	**Sandro Ruggiero**
11:15-11:45 am	Break	
11:45-12:30 am	Alternatives for Japanese 10-20 GeV muon ring, 1.5GeV proton source, and 10 GeV eRHIC	**Dejan Trbojevic**
12:30-2:15 pm	Break	
2:15-3:00 pm	New Muon Lattice - longitudinal emphasis	**Eberhard Keil**
3:00-3:30 pm	Break	
3:30-4:00 pm	FFAG gas filled muon cooling ring	**Alper Garren**
4:00-4:30 pm	Alternative 1.5 Gev proton lattice with x^2 nonlinearity	Ernest Courant

Friday 16 April		
What type of nonscaling muon lattice is optimal?		
9:00-10:00 am	Cost optimization of FFAGs	Scott Berg
10:00-10:15 am	Discussion	
10:15-10:50 am	Lattice optimization of FFAGs	Carol Johnstone
10:50-11:20 am	Break	
11:20-12:00 am	An analytic approach to FFAG optics	Michael Craddock
12:00 - 1:00 pm	Progress in lattice optimization of FFAGs	Shane Koscielniak
1:00 -1:15 pm	Workshop photograph	Corrie Kost
Design parameters for an electron model FFAG		
2:30 - 3:00 pm	Doublet, F0D0, Tripet, lattices for muon and electron FFAGs - low & high B-field, low & high volts/cell	Shane Koscielniak
3:00-3:30 pm	Electron model of an FFAG muon accelerator - doublet lattice	Eberhard Keil
3:30-4:00 pm	Break	
4:00-4:30 pm	Magnets for electron model	George Clark
4:30-5:15 pm	Comments on PRISM, etc	Yoshitaka Kuno

Saturday 17 April		
9:00-10:00 am	Injection & Extraction topics	Bob Palmer
10:00 -10:15 am	FFAG Project	Yoshi Mori
10:15 am -1 pm	Discussions	Andy Sessler

Monday 19 April		
9:00-9:30 am	Integer resonances and closed orbit distortions	Toshio Suzuki
9:30-10:10 am	Resonance Crossing Topics	Rick Baartman
10:10-10:50 am	Magnet Calculations	Stephen Kahn
10:50-11:20 am	Break	
11:20-11:40 pm	HFSS calculations of 200 MHz cavity	Amiya Mitra
11:40-12:00 am	Workshop Organization...	
2:00-3:00 pm	Work	
3:00-3:30 pm	Break	
3:30-5:30 pm	Work	

TRIUMF CONFERENCE ROOM (Main Office Building)

Tuesday 20 April		
9:15-10:00 am	Building the Taylor Map of a nonscaling FFAG with Lie Algebra and using Mathematica	Dobrin Kaltchev
10:00-10:30 am	Pre-FFAG 5 GeV Dogbone RLA	Alex Bogacz
10:30-11:00 am	3rd Harmonic & Muons	Bob Palmer
11:00-11:30 am	Break	
11:30 am - 1 pm	Work	
1:00-3:00 pm	Transfer to Board Room; Work	
3:00-4:00 pm	R&D activities on ADS and proposal of China Spallation Neutron Source (Auditorium) Part 1, Part 2, Part 3	ShouXian Fang
4:00-6:00 pm	Transfer back to Conference Room; Work	

ISAC2 Conference Room

Wednesday 21 April		
8:30-10:00 am	Workshop Summary & Discussion	Shane Koscielniak
10:00-10:15 am	Break	
10:15-10:30 am	Optimization of 1.5 GeV Proton FFAG	Sandro Ruggiero
10:30-10:45 am	Longitudinal phase space distortion	Eberhard Keil
10:45-11:00 pm	ICOOL Tracking of nonscaling FFAG with semi-realistic magnet end fields.	Bob Palmer
11:00-11:15 am	Cost/Optimization: scaling formulae for FFAG	Carol Johnstone
11:15-11:30 am	Lattices and optimization formulae Part 1, Part 2	Dejan Trbojevic
11:30 am	Close-down	
11:30 -11:45 am	Discussion - next video-conference?	Scott Berg

Workshop closes at 11:30 am, 21st April 2004.

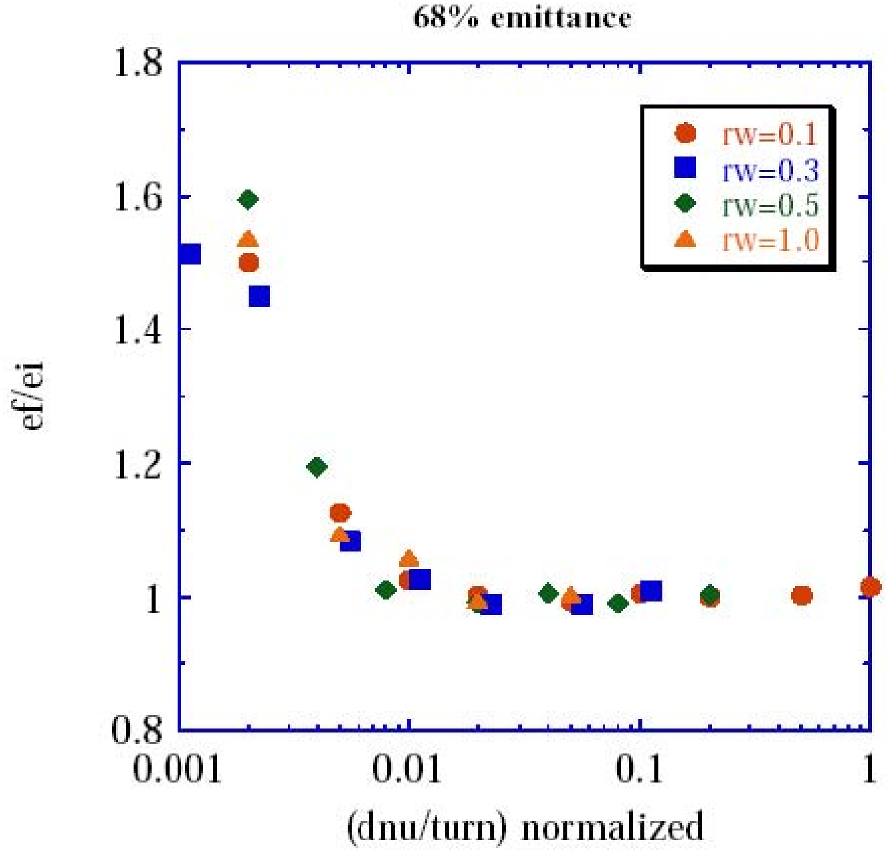
Resonance crossing and emittance growth

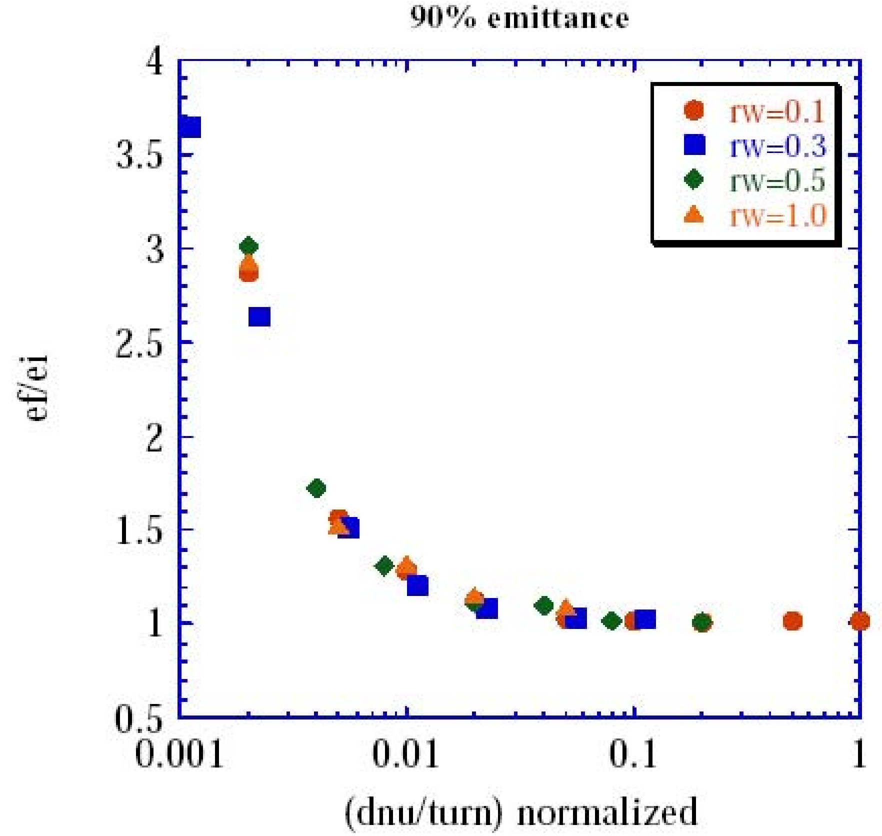
Shinji Machida
KEK

April 15, 2004 at TRIUMF

Shinji Machida

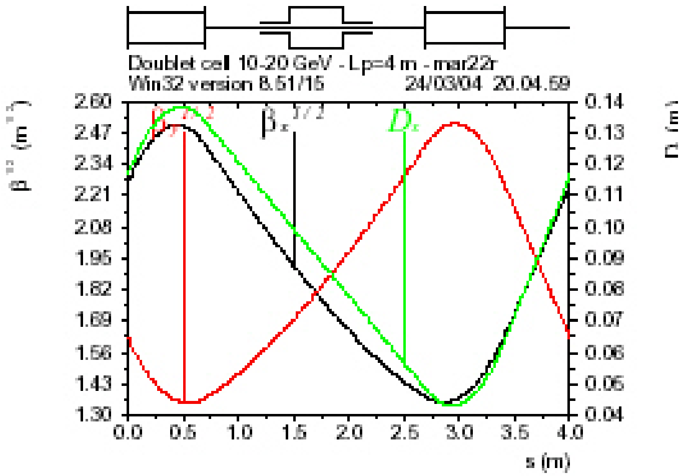
After normalization with k2^2 (at the BNL workshop)



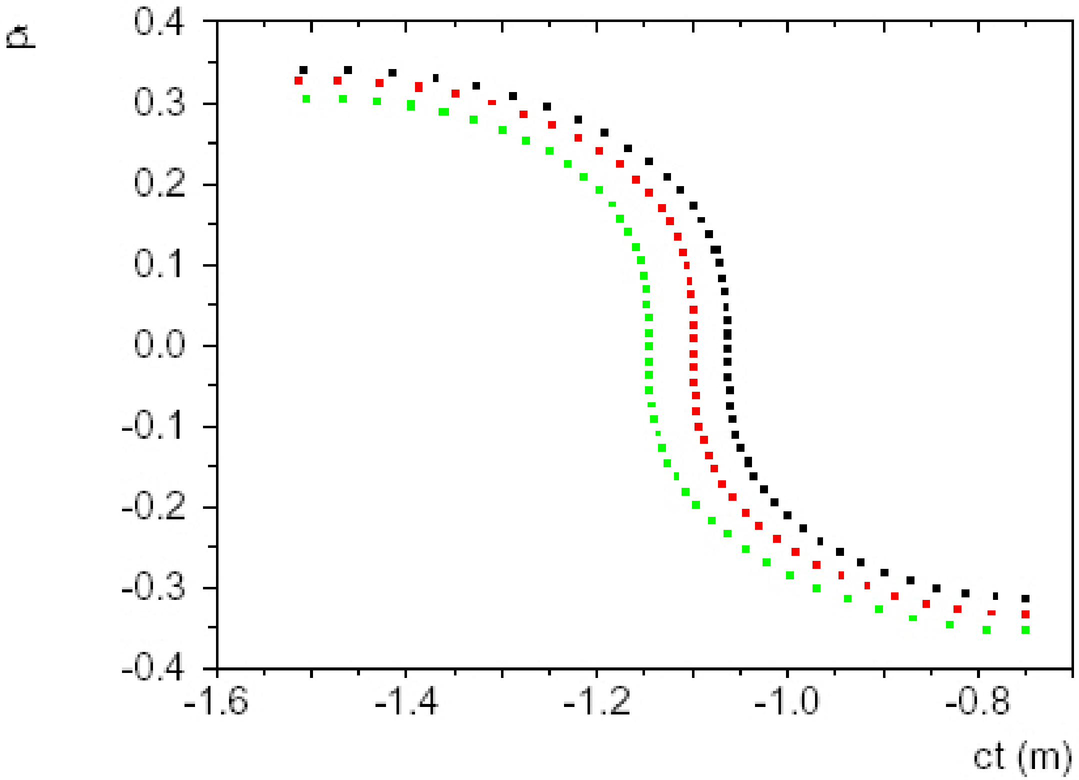


Keil-Sessler Doublet Lattice

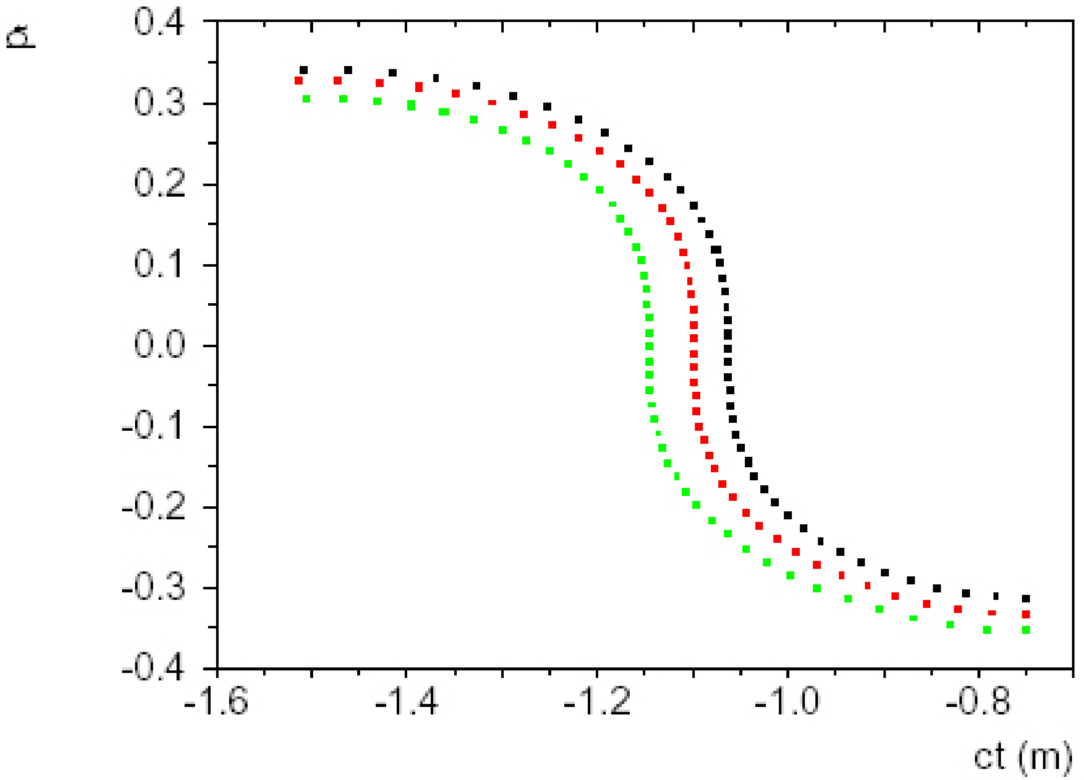
- Horizontally focusing gradient dipoles
- Vertically focusing gradient dipoles
- FODO lattice with $Q_x \approx Q_y$
- Space for super-conducting RF cavity



Acceleration in Keil-Sessler Doublet Lattice

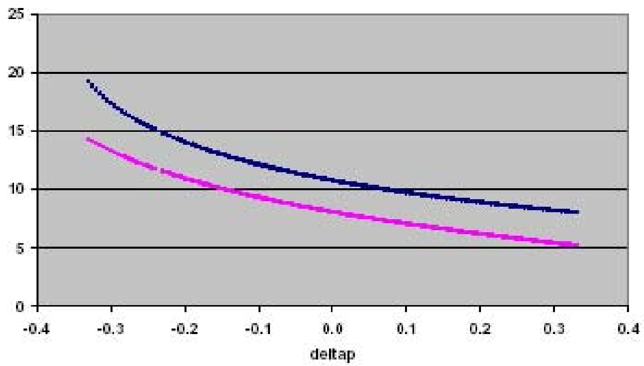


Acceleration in Keil-Sessler Doublet Lattice

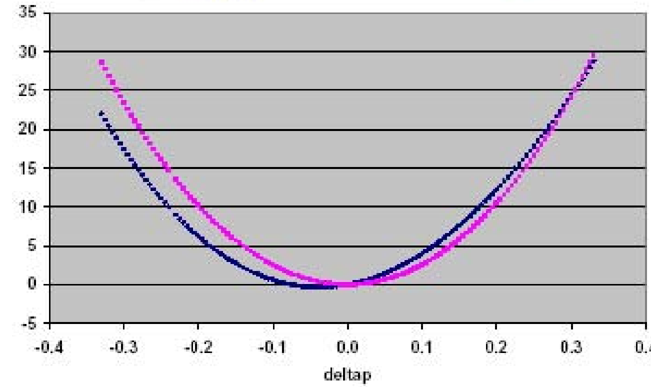


Doublet Figures

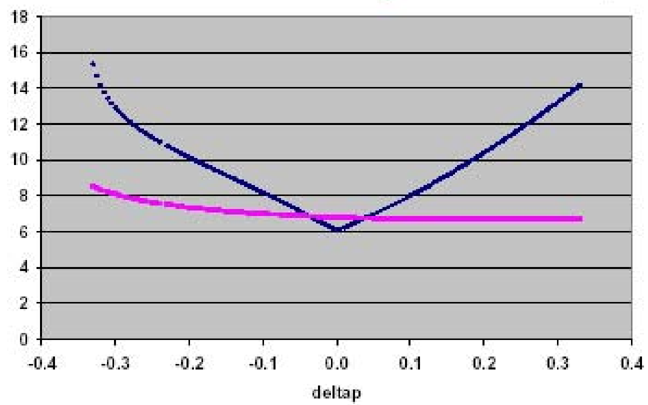
Tunes Q_x and Q_y vs. $\delta p/p$



Path length $\delta(s)$ and travel time ct in mm



Half apertures A_x and A_y in mm vs. $\delta p/p$



- Stable tunes q_x and q_y in range $-1/3 \leq \delta p/p \leq 1/3$
- $A_x < 20$ mm and $A_y < 10$ mm for $\varepsilon_n = 0.3$ mm, geometrical mean between ε_n in ATF and CLIC drive beam linacs
- Fit to ct yields $\eta_1 = 0.0167$

Joshi Mori

Practical Design

- Objects
  - Proton Driver
  - Electron Driver
  - Cancer Therapy
  - Muon Acceleration

Joshi Mori

Proton Driver

- Energy 1GeV
- Beam Current 1mA
- Repetition 1kHz(25Hz)

Joshi Mori

Proton Cancer Therapy

- Machine so far;Synchrotron,Cyclotron
- In order to make it more public, We need,
  - more beam
  - more compact size
  - less maintenance ability
  - less expensive cost

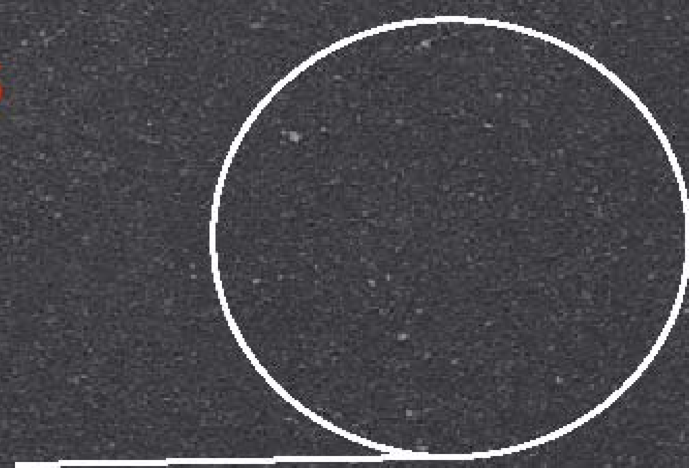
Joshi Mori

Space Charge Limit

- Synchrotron; Injection Energy ~ 7MeV
- Space Charge Limit ~ 4 x 10E11 ppp

10 times less!

Synchrotron is not enough.



Joshi Mori

Summary of proton therapy machine

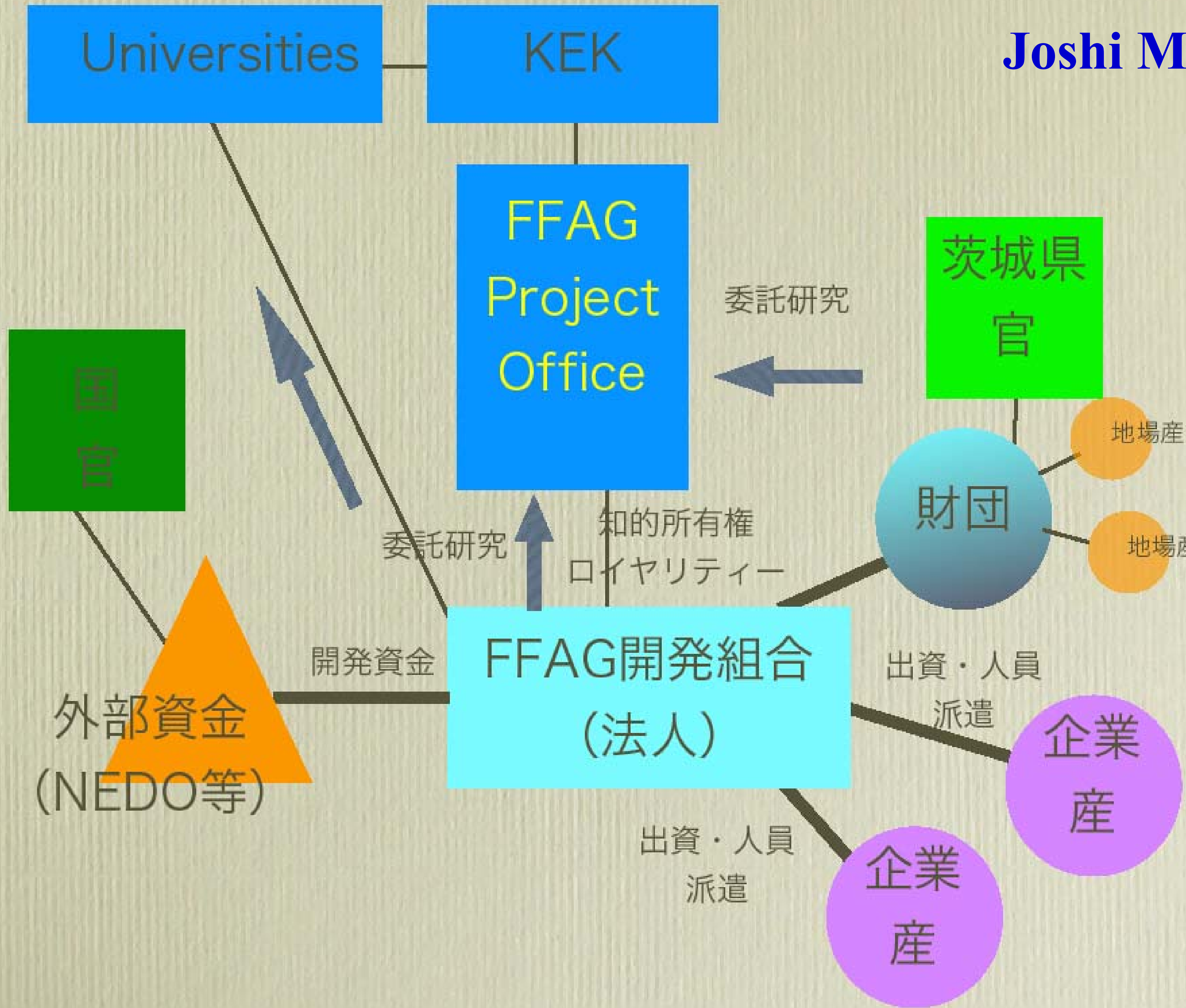
- Synchrotron

  Beam Intesity is not enough (respiration mode)

- Cyclotron

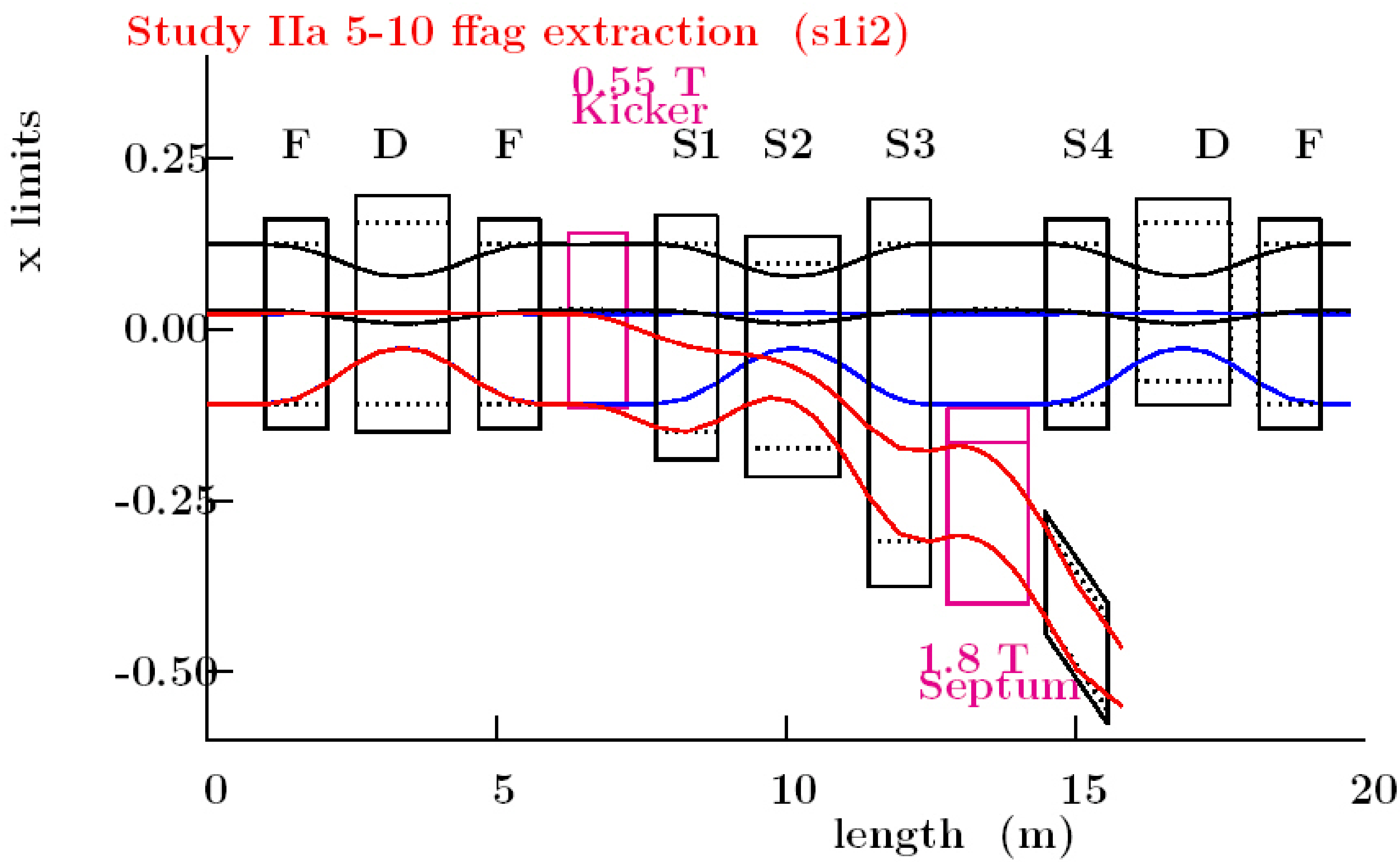
  Radiation Problem

Joshi Mori

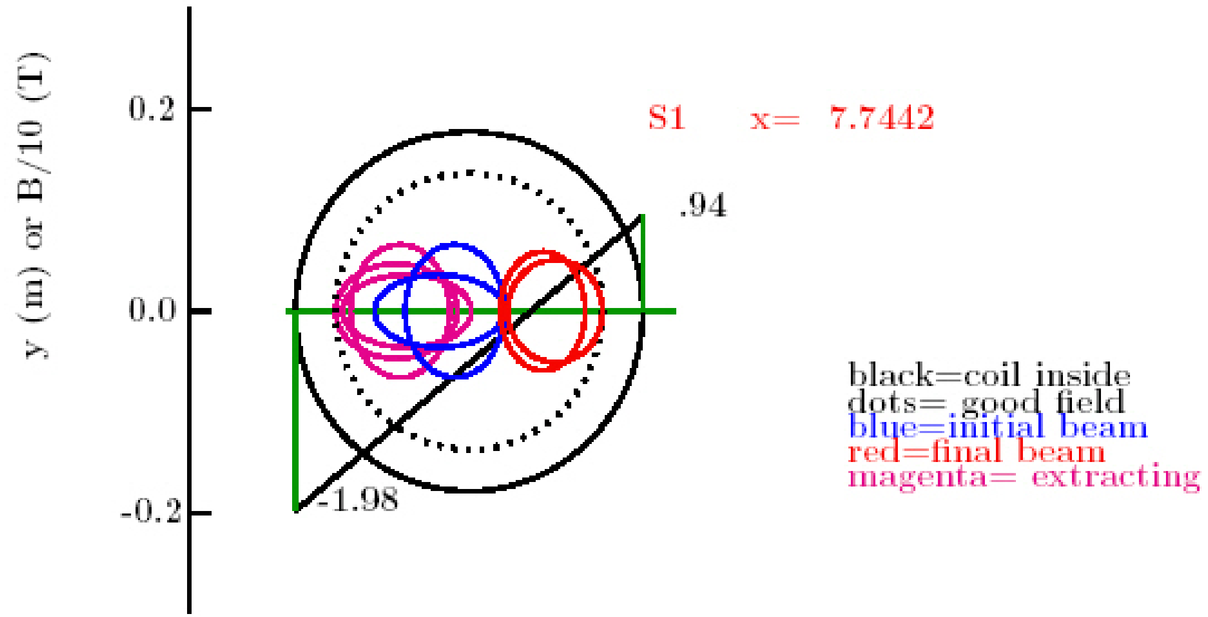

Universities
KEK
FFAG Project Office
委託研究
茨城県
官
国
官
地場産業
財団
地場産業
知的所有権
ロイヤリティー
委託研究
FFAG開発組合
(法人)
開発資金
外部資金
(NEDO等)
出資・人員
派遣
企業
産
出資・人員
派遣
企業
産

Bob Palmer

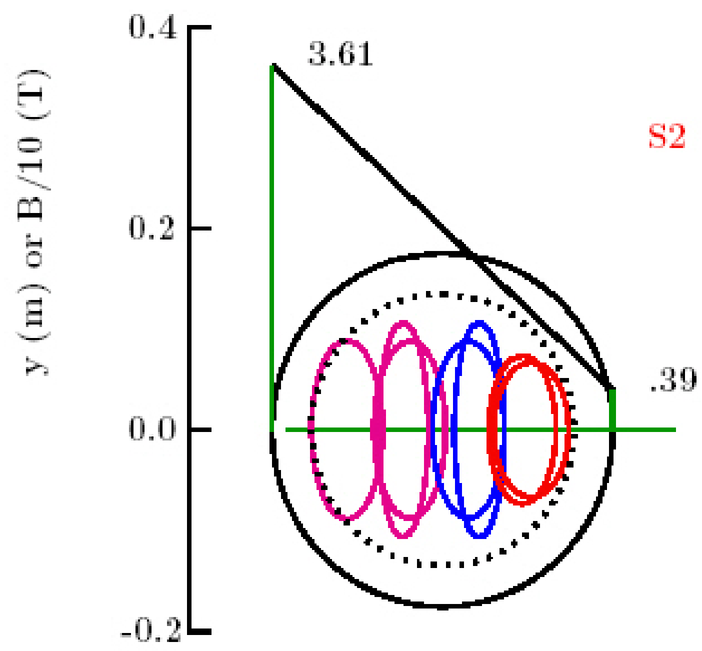
Injection from Inside



Bob Palmer



y (m) or B/10 (T)
0.2
0.0
-0.2
S1 x= 7.7442
.94
-1.98
black=coil inside
dots= good field
blue=initial beam
red=final beam
magenta= extracting

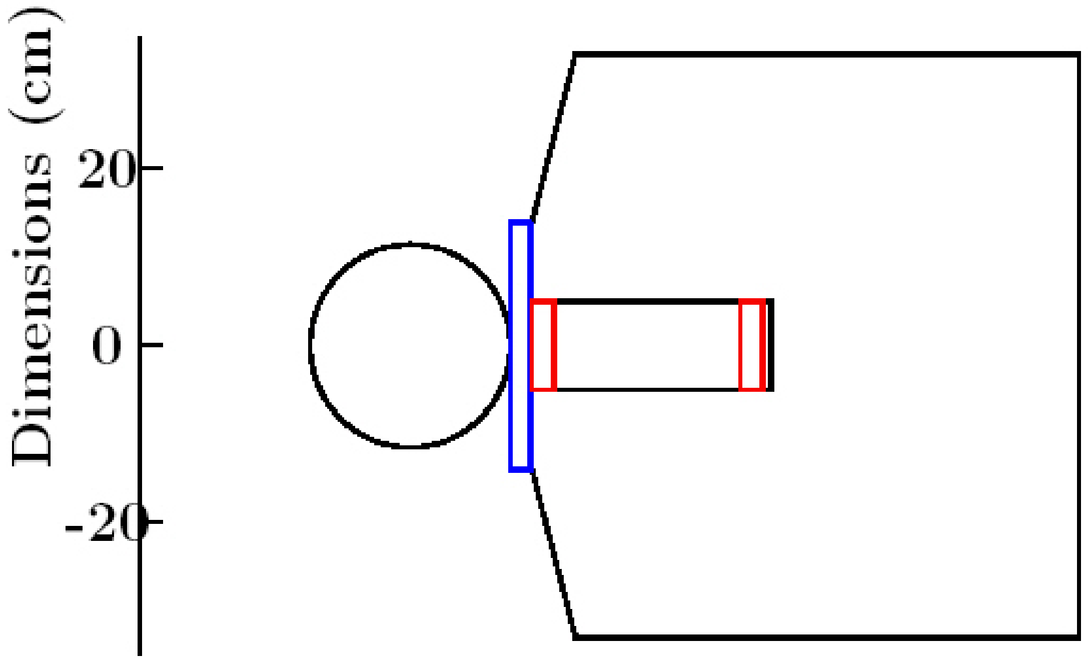


y (m) or B/10 (T)
0.4
0.2
0.0
-0.2
3.61
S2 x= 9.31
.39

Bob Palmer

Injection Septum Parameters

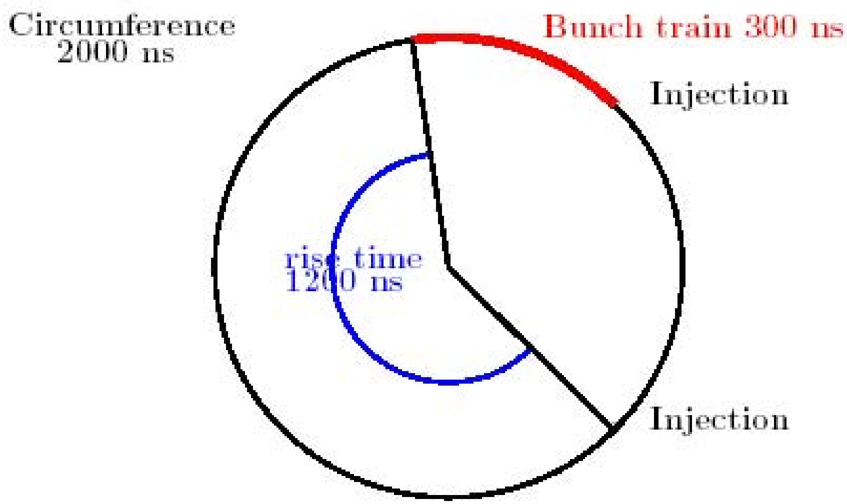
length	m	1.4
Field	T	1.8
Height	cm	10
Width	cm	23
septum	cm	5

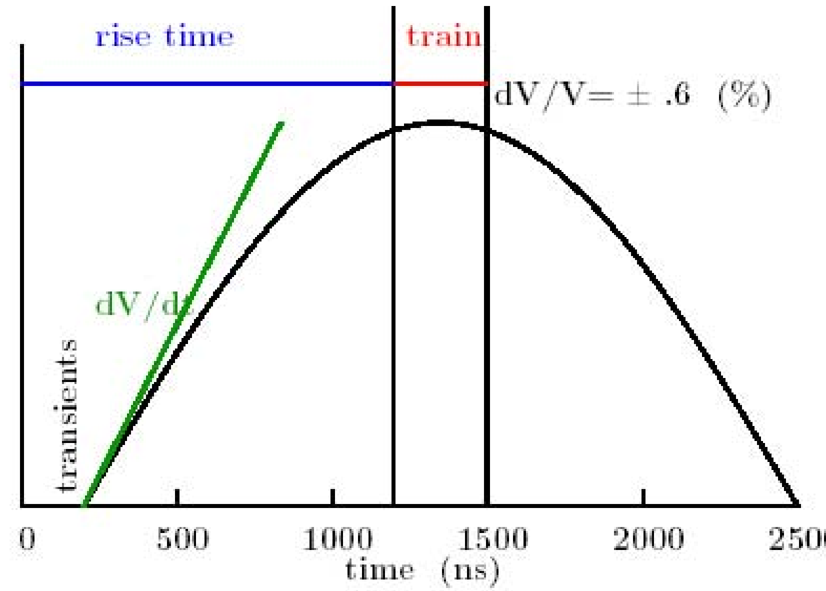


Bob Palmer

Required Rise time

Assume: Injection at +/- 45 degrees, Extraction at 0 degrees
e.g. for injection into 5-10 GeV ring





injection 5-10: $\mathrm{dt} = \left(\mathrm{circ} \times \frac{3}{4} - \mathrm{train} - \mathrm{transient}\right) \times \frac{2}{\pi} = 640 \quad \mathrm{ns}$

extraction 5-10: $\mathrm{dt} = \left(\mathrm{circ} \times \frac{4}{4} - \mathrm{train} - \mathrm{transient}\right) \times \frac{2}{\pi} = 950 \quad \mathrm{ns}$

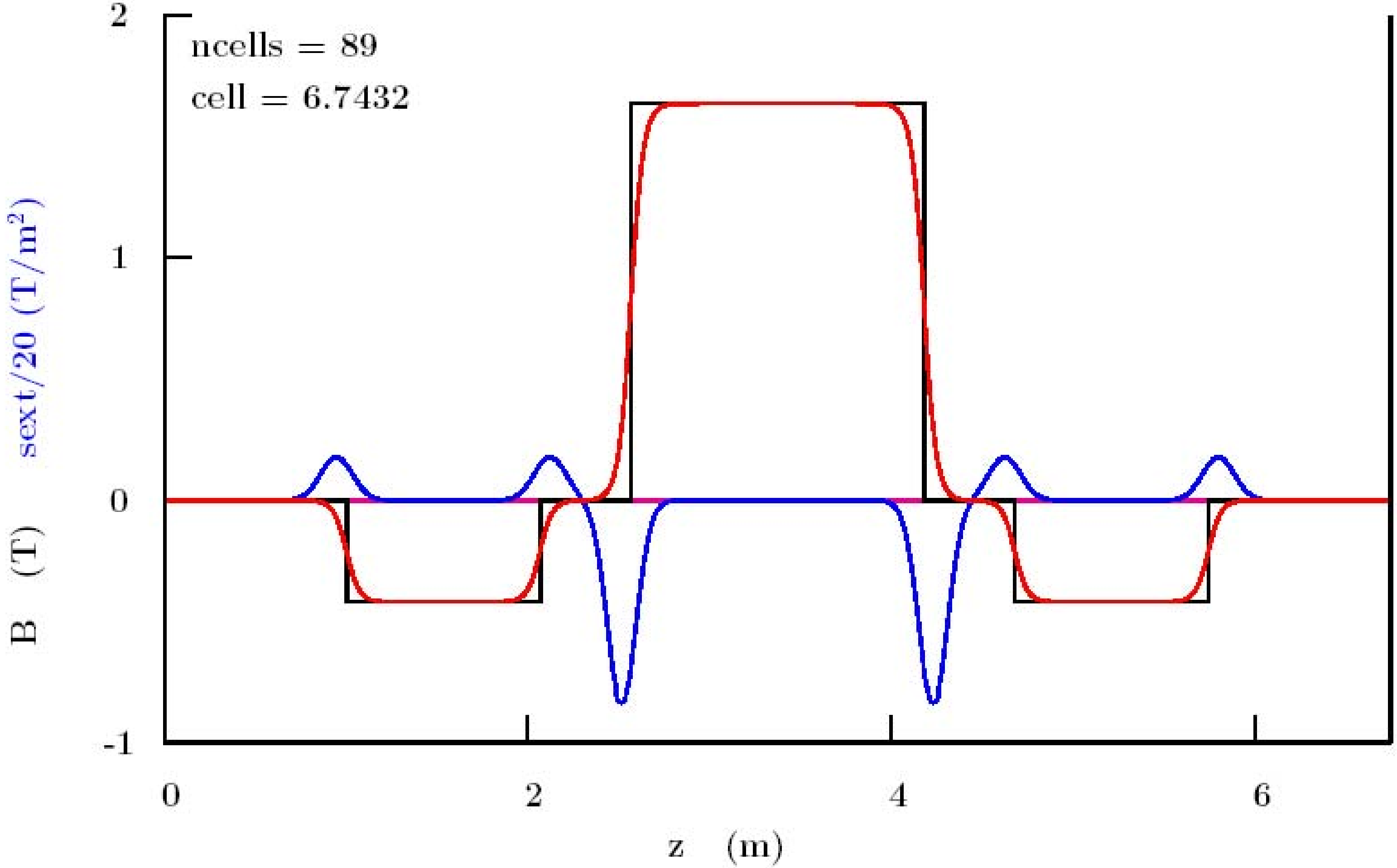
injection 10-20: $\mathrm{dt} = \left(\mathrm{circ} \times \frac{3}{4} - \mathrm{train} - \mathrm{transient}\right) \times \frac{2}{\pi} = 875 \quad \mathrm{ns}$

extraction 10-20: $\mathrm{dt} = \left(\mathrm{circ} \times \frac{4}{4} - \mathrm{train} - \mathrm{transient}\right) \times \frac{2}{\pi} = 1270 \quad \mathrm{ns}$

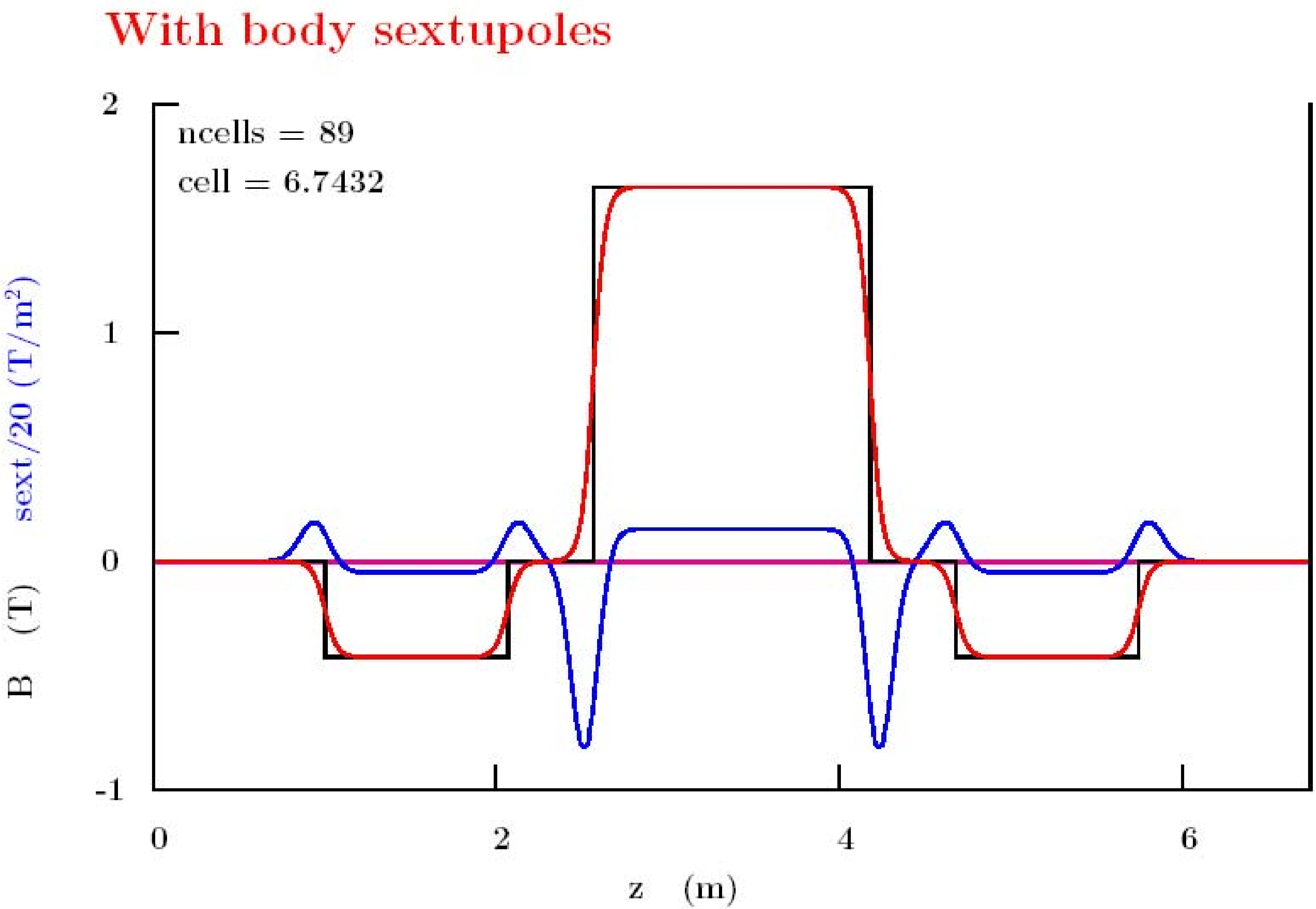
Bob Palmer

5-10 GeV Lattice

Without body sextupoles



Bob Palmer – with body sextp.

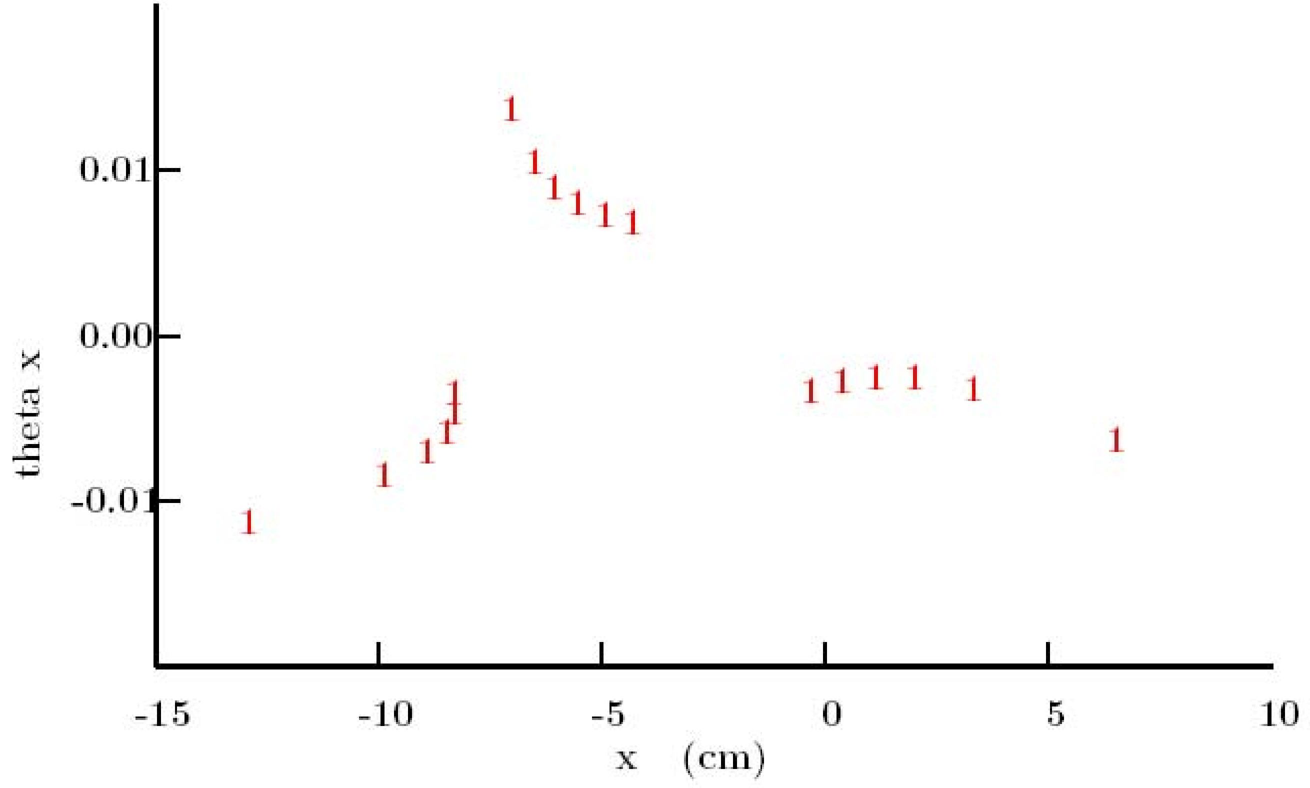


Bob Palmer

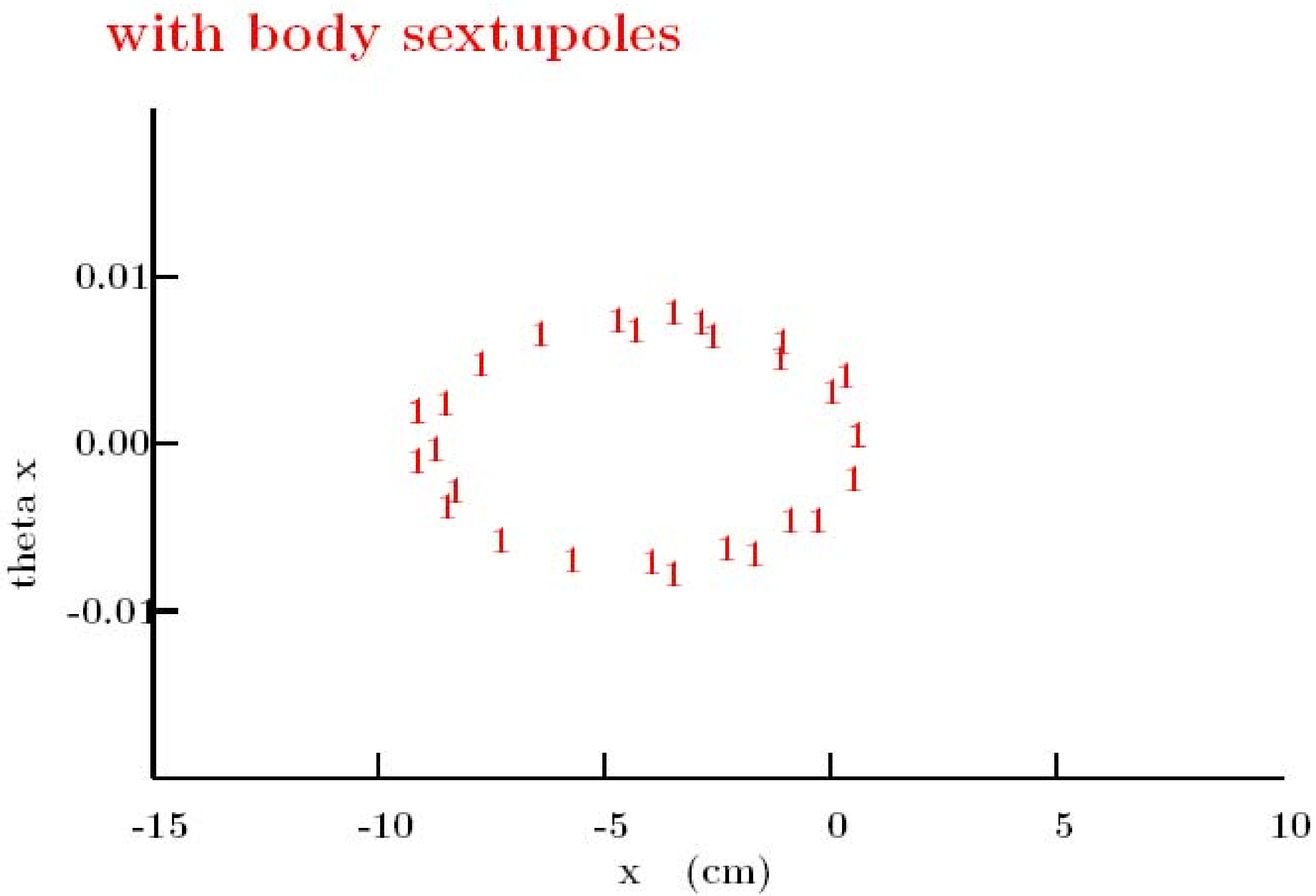
3rd order resonance at 5.1 GeV

e.g. inject single particle at edge (in x and y) of 30 pi mm acceptance. Observe phases after each turn.

without body sextupoles



Bob Palmer

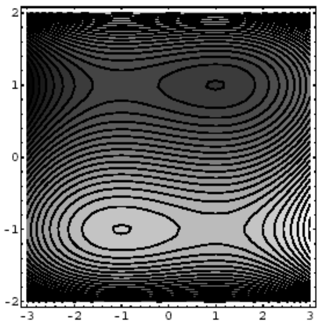


Shane Koscielniak

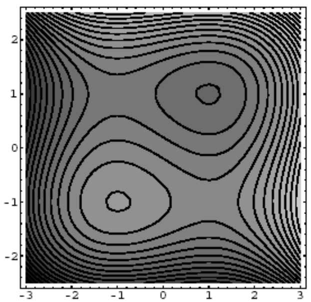
Bi-parabolic Oscillator

Topology discontinuous at $a = 1$

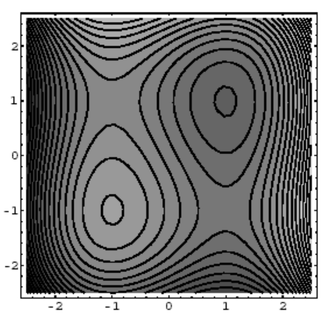
- For $a < 1$ there is a sideways serpentine path
- For $a > 1$ there is a upwards serpentine path
- For $a \equiv 1$ there is a trapping of two counter-rotating eddies within a background flow.



a=1/10



a=1/2

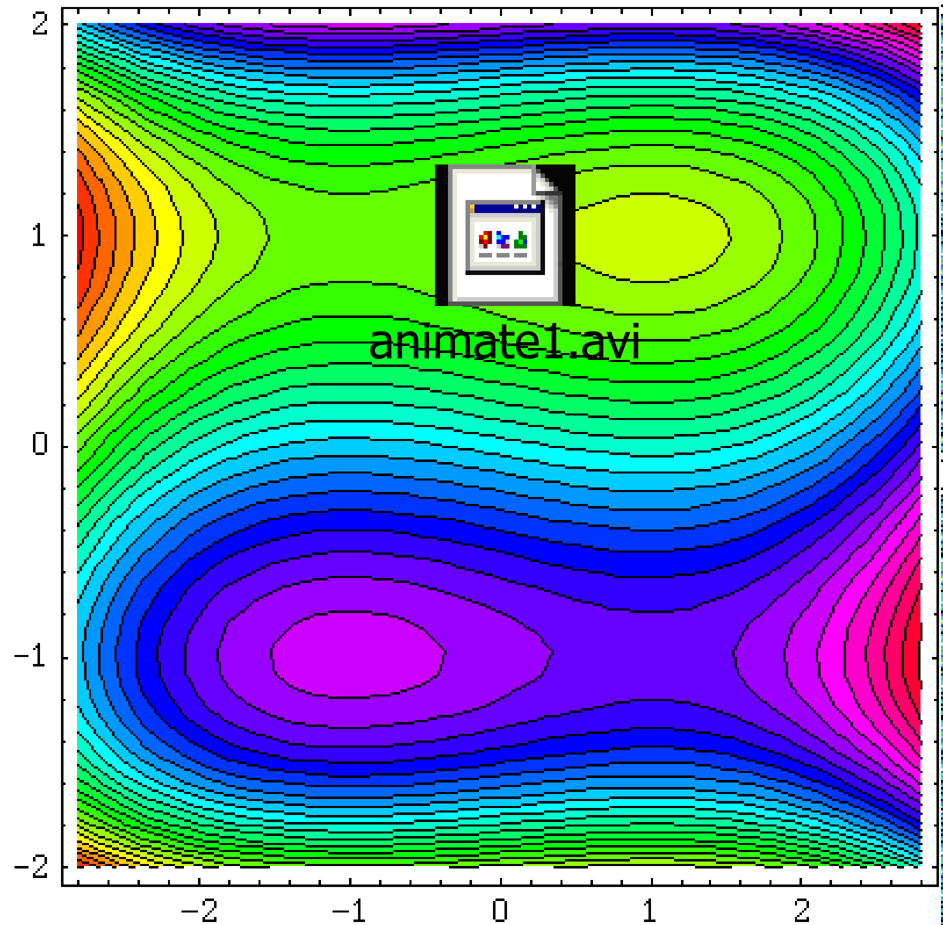


a=1

a=2

Condition for connection of libration paths: $a \geq 1$

Phase space of the equations $x'=(1-y^2)$ and $y'=a(x^2-1)$



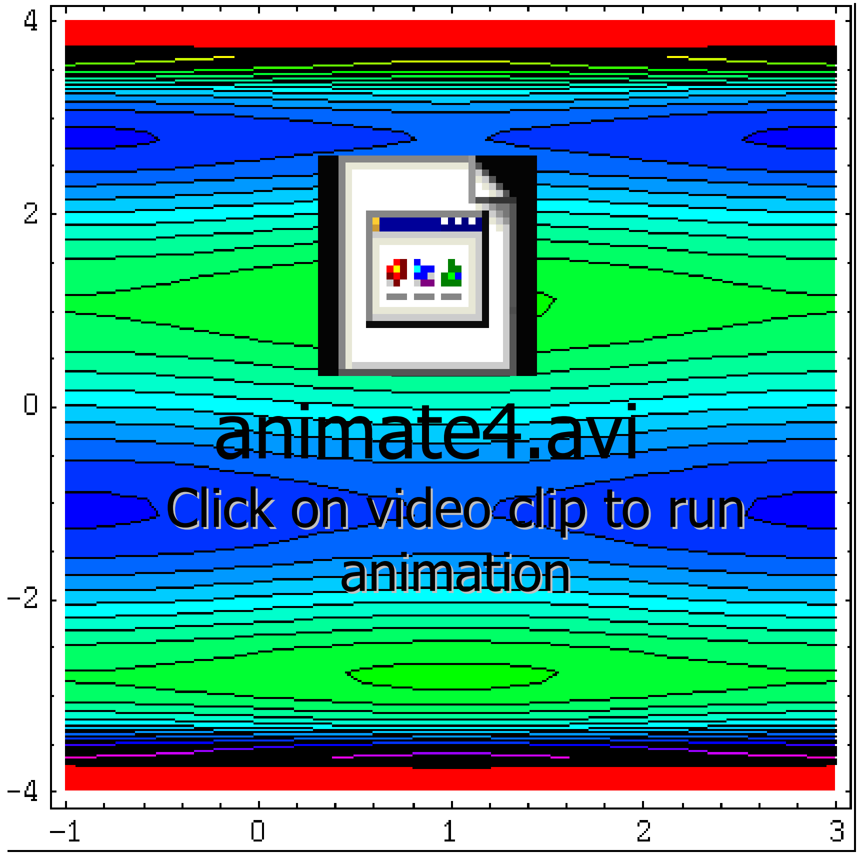
Animation: evolution of phase space as strength 'a' varies.

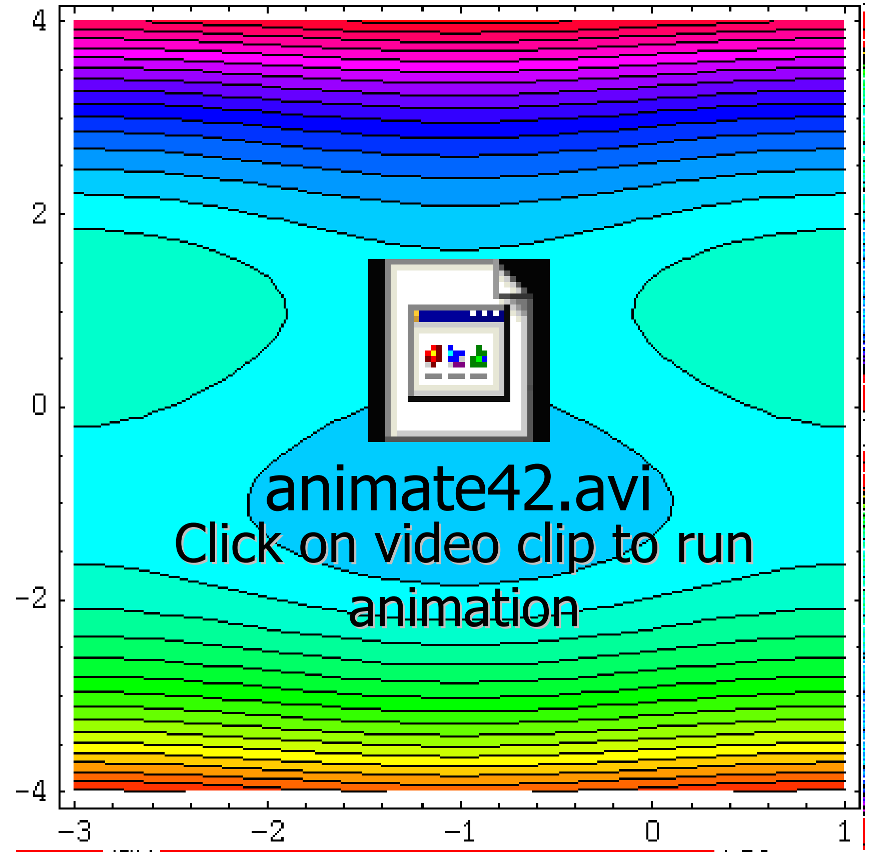
Shane Koscielniak

Quartic Pendulum Oscillator

Phase space of the equations
$x' = y^2(1 - b^2 y^2) - 1$
and $y' = a.\mathrm{Cos}(x)$

Animations: evolution of phase space as strengths `*a,b*` vary.





Parameter `*a*` is varied from 0.1 to 2.9 while `*b*` held fixed at *b*=1/3.

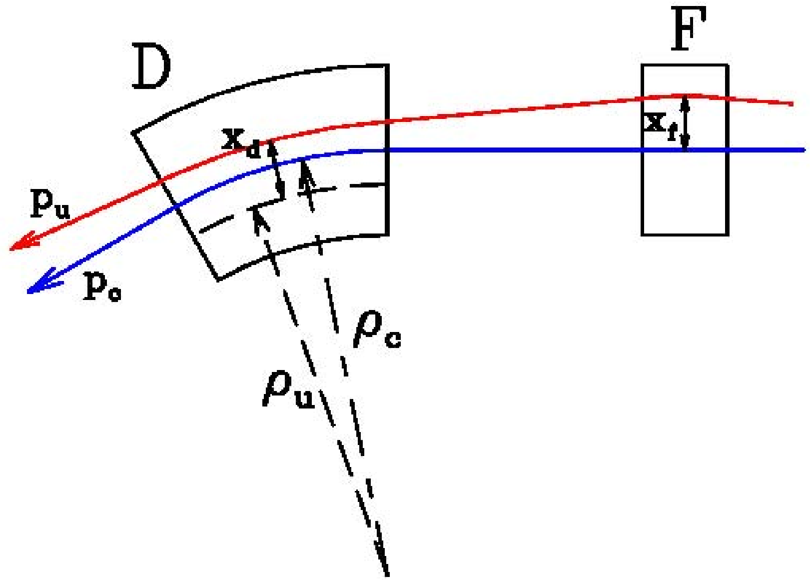
Parameter `*b*` is varied from to 0.1 to 0.5 while `*a*` held fixed at *a*=3/4.

Remember to close media player before proceeding to next slide/animation

Shane Koscielniak

Closed orbits

Simple example: F0D0 cell with D-sector and F-quad.



- l_0 is the drift length. l_f, l_d are F-quad and D-sector half-lengths. $k = \sqrt{B_1 c/p}$ where B_1 is the gradient. $\sigma = k \times l$.

- At entrance to the D sector, the coordinate jumps by an amount $\delta\mathbf{r} = (\delta\rho, 0)$ where $\delta\rho = (\rho_u - \rho_c)$ – because of difference between p_u and p_c coordinate systems.

- Transform the input vector $\mathbf{x}_0 = (x_0, 0)$ from the entrance of the half F quadrupole, to the exit of the half D sector. $\mathbf{D}, \mathbf{F}, \mathbf{O}$ are matrices.

$$(x, x') = \mathbf{D}_x(k_r l_d)\left[-\delta\mathbf{r} + \mathbf{O}(l_0) \cdot \mathbf{F}_x(k_f l_f) \cdot \mathbf{x}_0\right] \ . \tag{9}$$

- The value of x_0 that will make $x' = 0$ is the closed orbit.

Shane Koscielniak

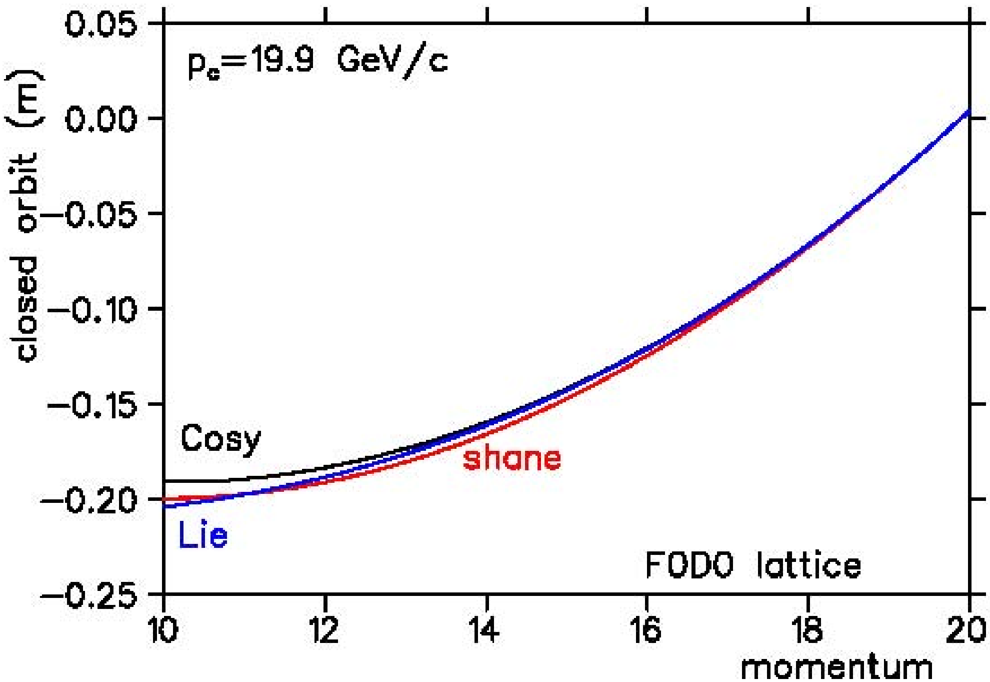
- At the centres of the full F and full D quadrupoles

$$x_f = (\rho_c - \rho_u)\mu_r \sinh\sigma_r / D \qquad \text{w.r.t. } \rho_c \tag{10}$$

$$x_d = (\rho_c - \rho_u) k_f \rho_c \omega_u \sin\sigma_f / D \qquad \text{w.r.t. } \rho_u \tag{11}$$

$$D = k_f \rho_c \omega_u \cosh\sigma_r \sin\sigma_f - \mu_r \sinh\sigma_r (\cos\sigma_f - k_f l_0 \sin\sigma_f)\ . \tag{12}$$

Working is increasingly more complex for Triplet and Doublet, but analgous expressions may be found; and from these path length may be obtained by Pythagoras theorem and integration.

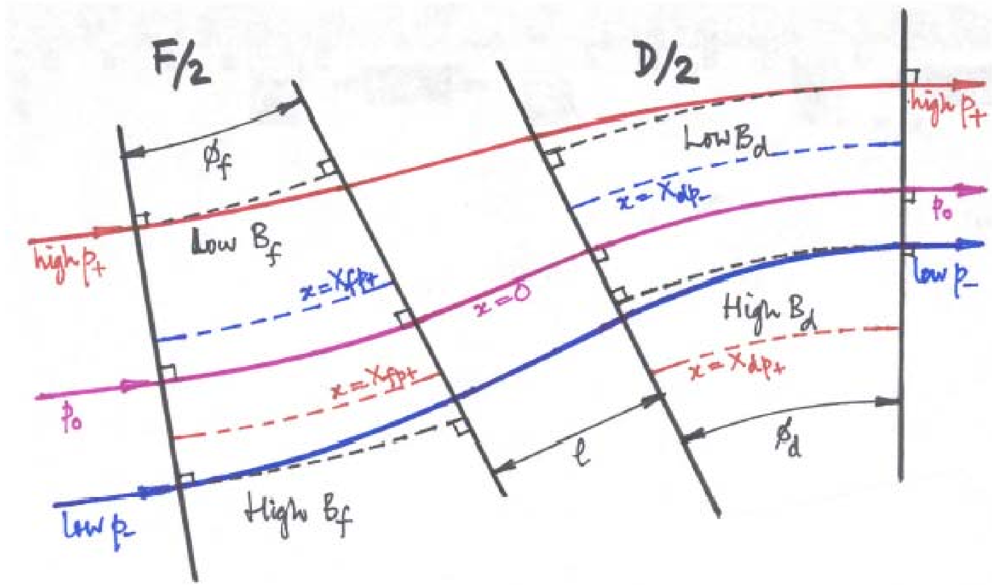


Comparison of closed orbit predictions:
COSY vs Lie/Kaltchev vs analytic/Shane

Mike Craddock

ORBITS IN FDF SECTOR GRADIENT MAGNETS

The figure shows a half cell:



Each magnet has an equilibrium orbit for each momentum p

- a circular arc (radius ρ_{fp}, ρ_{dp}) with constant field B_{fp}, B_{dp}
- offset by X_{fp}, X_{dp} w.r.t. the reference orbit $x = 0$:

$$\boxed{X_p = \frac{r_0}{2n_0}\left\{(1-n_0)+\sqrt{(1-n_0)^2 - 4n_0(\Delta p/p_0)}\right\}}$$

where $$n_0 = -\frac{r}{B}\frac{dB}{dr}\bigg|_{p_0}$$

For a whole cell, the orbit consists of:

- long and short drifts;
- betatron oscillations
  - sinusoidal in F of amplitude $A_f = x_{f\perp} - X_{fp}$ about X_{fp},
  - hyperbolic in D of amplitude $A_d = x_{d\perp} - X_{dp}$ about X_{dp}.
  - where $x_{f\perp}$ and $x_{d\perp}$ are the offsets at the normal-crossing edge.

Mike Craddock

ORBIT LENGTH

Integrating along the various orbit segments (F, D, short drift), we find the following deviations in path length between momenta p and p_0 (the reference orbit):

$$\Delta s_f \cong -\left(X_{fp} + A_f\right)\phi_f + \frac{A_f}{\sqrt{1-n_f}}(\alpha - \sin\alpha) + \frac{\sqrt{1-n_f}\,A_f^2}{8\rho_{f0}}(2\alpha - \sin 2\alpha)$$

$$\Delta s_d \cong \left(X_{dp} + A_d\right)\phi_d + \frac{A_d}{\sqrt{n_d - 1}}(\sinh\alpha - \alpha) + \frac{\sqrt{n_d - 1}\,A_d^2}{8\rho_{d0}}(\sinh 2\alpha - 2\alpha)$$

$$\Delta s_\ell = \ell\left(\sec\chi_{fd} - 1\right)$$

Terms of higher order in A_f/ρ_{f0} and A_d/ρ_{d0} are negligible and have been discarded.

The formulae for offsets x and path length variation Δs give results in excellent agreement with lattice codes.

Mike Craddock

10 GeV/c	Dejan FDF Triplets			Scott FDF	F0D0-1	F0D0-2
Circumference C (m)	323	328	348	481.7	612.2	470
E.O. offset X_{d10} (m) for D	0.0480	0.0398	0.0335	0.0500	0.0545	0.0803
Osc'n amplitude A_d (m)	0.0458	0.0387	0.0330	0.0474	0.0470	0.0694
Offset $x_{d\perp}$ (m) - formula	0.0022	0.0011	0.0005	0.0026	0.0075	0.0109
" " " " " - lattice code	0.0024	0.0010	0.0005	0.0031	0.0077	0.0116
" " " " " - difference	-0.0002	0.0000	0.0000	-0.0004	-0.0003	-0.0007
E.O. offset X_{f10} (m) in F	0.0141	0.0107	0.0089	0.0178	0.0163	0.0250
Osc'n amplitude A_f (m)	0.0436	0.0361	0.0306	0.0459	0.0503	0.0751
Offset $x_{f\perp}$ (m) - formula	-0.0295	-0.0255	-0.0217	-0.0281	-0.0340	-0.0501
" " " " " - lattice code	-0.0290	-0.0250	-0.0213	-0.0270	-0.0331	-0.0478
" " " " " - difference	-0.0006	-0.0005	-0.0004	-0.0010	-0.0009	-0.0024
Extra path ΔC (m) - thin lens	0.2393	0.1974	0.1675	0.2340	0.2247	0.3293
" " " " " " " - formula	0.1339	0.1050	0.0873	0.1793	0.2197	0.3303
" " " " " " - lattice code	0.1434	0.1165	0.0992	0.1943	0.2382	0.3442
" " " " " " - difference	-0.0095	-0.0115	-0.0119	-0.015	-0.0184	-0.0139

Rick Baartman: Fast Crossing of Betatron Resonances

Hamiltonian

"Smoothed" Hamiltonian with n harmonic, m order driving term

$$H = \frac{p^2}{2} + \frac{Q^2 x^2}{2} + n\frac{b_{n,m} x^m}{m}\cos(n\theta + \phi)$$

Independent variable is θ, the azimuth around the ring. We let the tune Q be a (slow) function of θ. We are interested in the resonance at $mQ = n$. Equation of motion: $x'' + Q^2 x = -nb_{n,m} x^{m-1}\cos(n\theta + \phi)$. $b_{n,m}$is a strength parameter: $nb_{n,m+1} = \frac{\overline{R}}{\overline{B}}\frac{1}{m!}\frac{\partial^m B_n}{\partial x^m}$

Action-angle variables (J, ψ):

$$x = \sqrt{2J/Q}\cos\psi,\ p = \sqrt{2JQ}\sin\psi \qquad (1)$$

New Hamiltonian:

$$H = QJ + \frac{nb_{n,m}}{m}\left(\frac{2J}{Q}\right)^{m/2}\cos^m\psi\cos(n\theta + \phi)$$

Rick Baartman: Fast Crossing of Betatron Resonances

The action equation is a little simpler if we revert to $A = \sqrt{2J/Q_0}$, the betatron amplitude:

$$\frac{A'}{A^{m-1}} = \frac{nb_{n,m}}{2^m Q_0} \sin(mQ'\theta^2/2 - \phi)$$

We see that we get a Fresnel integral. The largest amplitude gain occurs for phase $\phi = \pi/4$:

$$\frac{\Delta(A^{2-m})}{2-m} = \frac{nb_{n,m}}{2^m Q_0} \sqrt{\frac{2\pi}{mQ'}}$$

Note $Q_0 = n/m$. Also, we prefer the tune change per turn, $Q_\tau \equiv 2\pi Q'$,

$$\frac{\Delta(A^{2-m})}{2-m} = \frac{\pi}{2^{m-1}} b_{n,m} \sqrt{\frac{m}{Q_\tau}}$$

Of course this does not hold for $m = 2$; in that case, the LHS is $\Delta(\log A)$.

Rick Baartman: Fast Crossing of Betatron Resonances

Integer resonance $m = 1$

$$\Delta A = \pi \frac{b_{n,1}}{\sqrt{Q_\tau}} = \frac{\pi}{\sqrt{Q_\tau}} \frac{\overline{R}}{\overline{B}} \frac{B_n}{Q}$$

This appears in early cyclotron theory because the $Q = 1$ resonance was used to extract the beam. See for example [Al Garren et al, Nucl. Instr. Meth. **18,19** (1962) p. 543].

Keil-Sessler doublet lattice: Worst (smallest) Q_τ appears to be ~ 1, at energy 20 GeV; $\epsilon_n = 1.7$ mm so $\epsilon = 10\,\mu$m, $A = 6$ mm and we would want ΔA less than about a tenth of this. $\overline{B} = B\rho/R = 1$ T. So we find

$$B_n < 400\,\text{Gauss},$$

where $n = Q$. This seems OK.

Rick Baartman: Fast Crossing of Betatron Resonances

Half-integer, $m = 2$

The formula

$$\log \frac{A_{\rm f}}{A_{\rm i}} = \frac{\pi}{\sqrt{2}} \frac{b_{n,2}}{\sqrt{Q_\tau}}$$

was verified experimentally in the TRIUMF cyclotron [R. Baartman, G.H. Mackenzie, M.M. Gordon, $10^{\rm th}$ Int. Conf. on Cyclotrons and Apps. (1984) p. 40]Link.

$b_{n,2} = \frac{\overline{R}}{n\overline{B}} \frac{\partial B_n}{\partial x}$, where $n = 2Q$, applied to the Keil-Sessler doublet FFAG and as before allowing only a 10% growth in amplitude, gives

$$\frac{\partial B_n}{\partial x} < 200 \text{ G/m}$$

Or, more precisely, for non-smooth case,

$$\left| \beta_x \frac{\partial B}{\partial x} \right|_{n=2Q} < 800 \text{ G}$$

Rick Baartman: Fast Crossing of Betatron Resonances

1/3-integer, $m = 3$

$$\Delta\left(\frac{1}{A}\right) = \frac{\sqrt{3}\,\pi}{4}\frac{b_{n,3}}{\sqrt{Q_\tau}}$$

or, more precisely,

$$\Delta\,\epsilon^{-1/2} = \frac{\pi}{4\sqrt{3}}\frac{1}{\sqrt{Q_\tau}}\frac{R}{B\rho}\left|\beta_x^{3/2}\frac{\partial^2 B_z}{\partial x^2}\right|_{n=3Q}$$

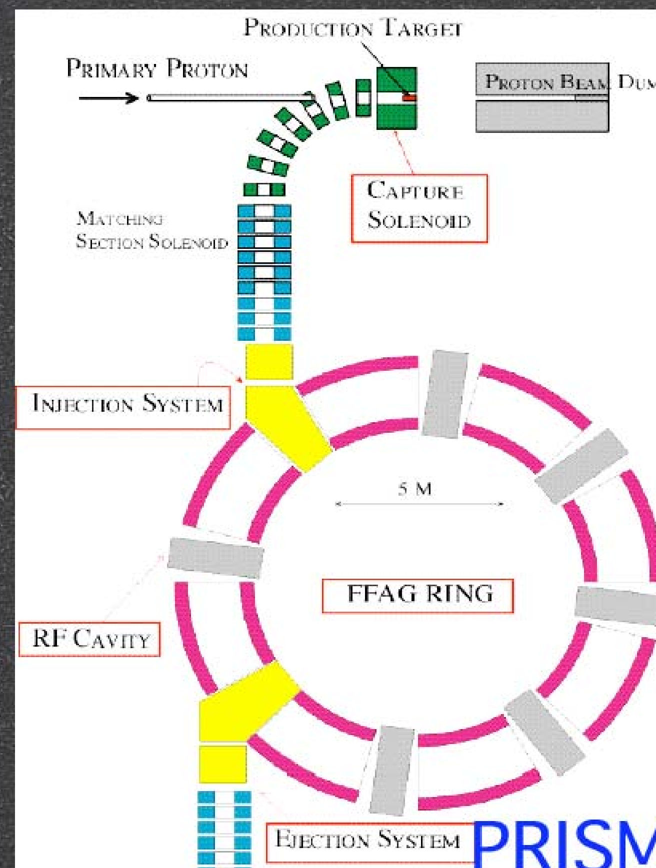
The trend for resonances is that they are less dangerous the higher the order, so one would expect the imperfection third order resonances to be easily crossed. However, most proposed muon FFAGs traverse a cell tune of 1/3. This is the **intrinsic** resonance $3Q = N_{\mathrm{cells}}$. Even a slight systematic sextupole component will result in very large $b_{n,3}$ when $n = N_{\mathrm{cells}}$.

Kuno Joshikata: Physics Potential of Muon and Neutrino Factory Based on FFAG's

What are Muon and Neutrino Factories ?

Muon Factory

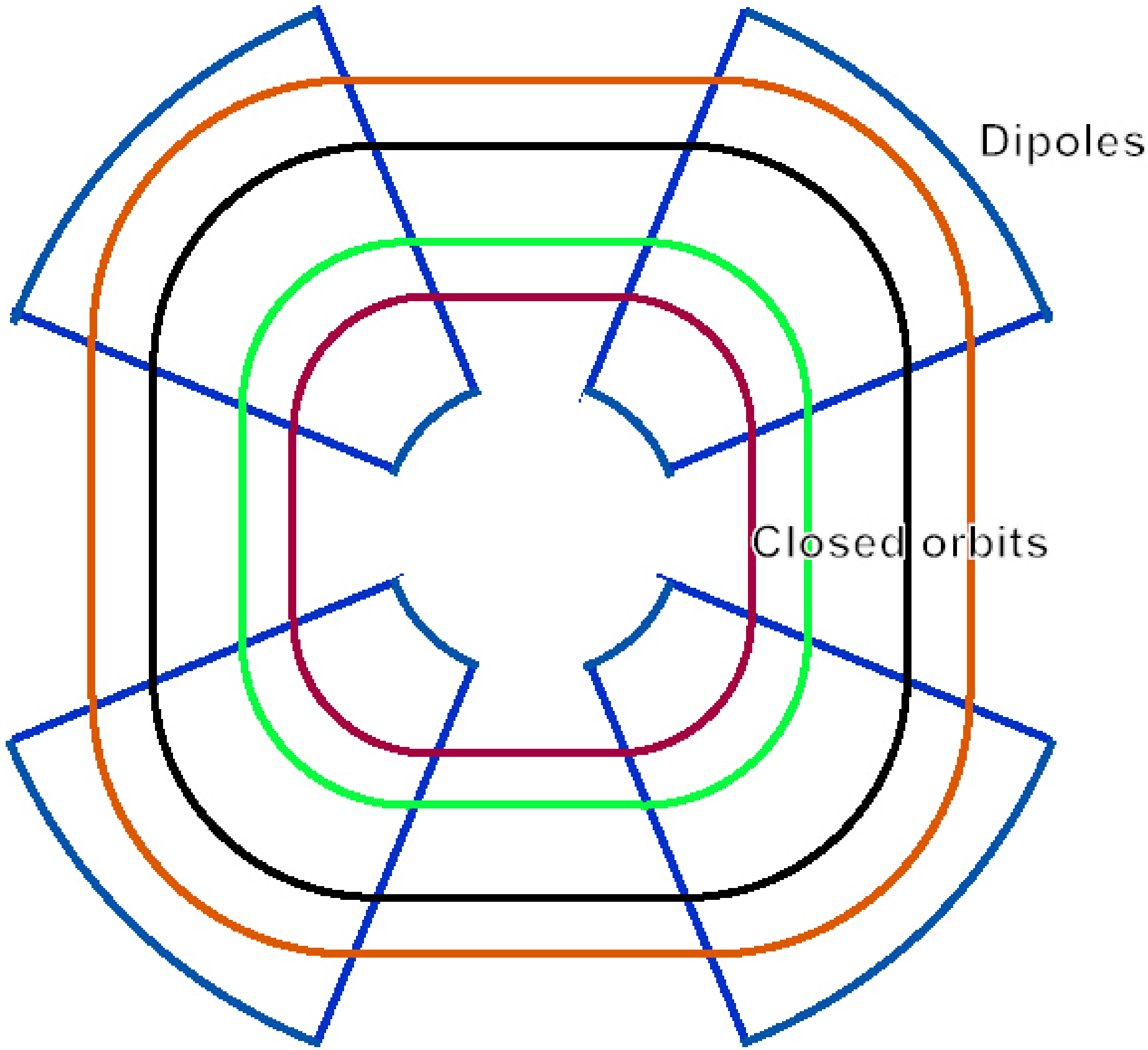
- high intensity
  - $10^{12} - 10^{14} \mu^{\pm}/sec$
  - a MW proton machine needed
- high brightness
  - narrow E width
  - beam treatment (FFAG)
- high purity (no pions)
- dedicated to types of experiments?



Alpert Garren:

4-DIPOLE WEAK-FOCUSING RING

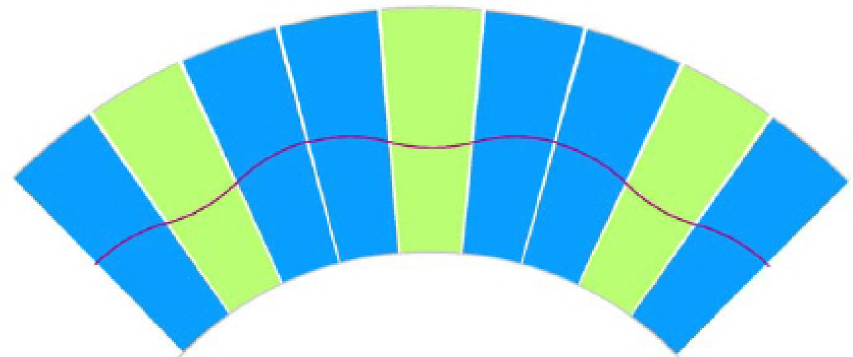
= / Rc = 1

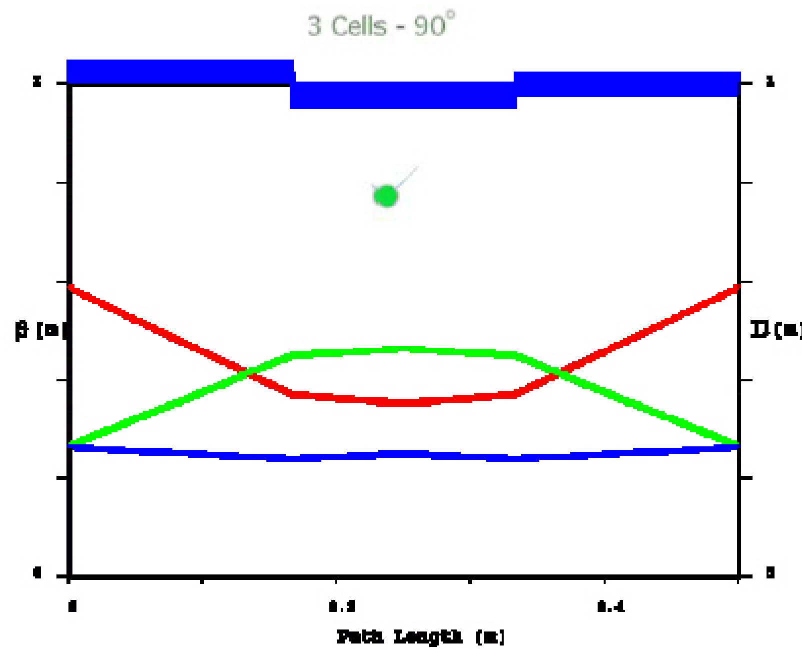


Alpert Garren:

An FFAG-like Lattice

Lattice consists of alternating Horz. Defocusing and Horz. Focusing with $L_{HD} = \frac{1}{2} L_{HF}$. No drift cells between dipole elements.





Parameters

12 cells
Bend angles 30° and –15°
Circumference = 6m
B_o = 2.6T and P_o = 250 MeV/c
Dispersion = 25 cm

Carol Johnstone

10-20 GeV Derived Non-scaling FFAGs: Examples

Muon Collaboration

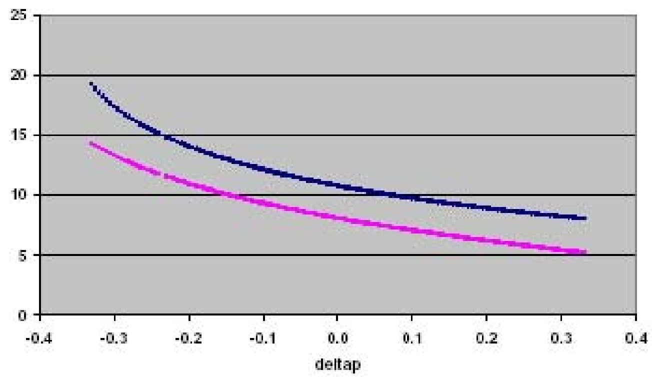
	FDF-triplet	FODO
Circumference	607m	616m
#cells	110	108
cell length	5.521m	5.704m
D-bend length	1.89m	1.314m
F-bend length	0.315m (2!)	0.390
F-D spacing	0.5 m	0.5m
Central energy	20 GeV	18 GeV
F gradient	60 T/m	60 T/m
D gradient	20 T/m	18 T/m
F strength	0.99	0.9384
D strength	0.300	0.300
Bend-field (central energy)	2 T	2.7 T
Orbit swing		
Low	-7.7	-9.8
High	0	3.8
ΔC (pathlength)	16.6	26
βxmax/βymax (10 GeV)	6.5/13.8	14.4/11.44
β(injection straight)	6.5	5.8

Motivation of Electron Model

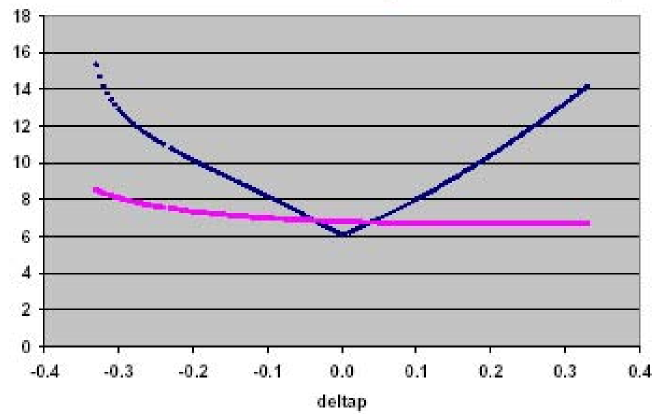
- Demonstrate novel features of acceleration in non-scaling FFAG rings at fraction of cost of FFAG rings in neutrino factory
  - Acceleration outside buckets
  - Crossing of many integral and half-integral resonances
- Electron models
  - accelerate from about 10 to about 20 MeV
  - have focusing by doublets or triplets
  - fit into a small hall
  - are constructed next to a suitable electron linac

Doublet Figures

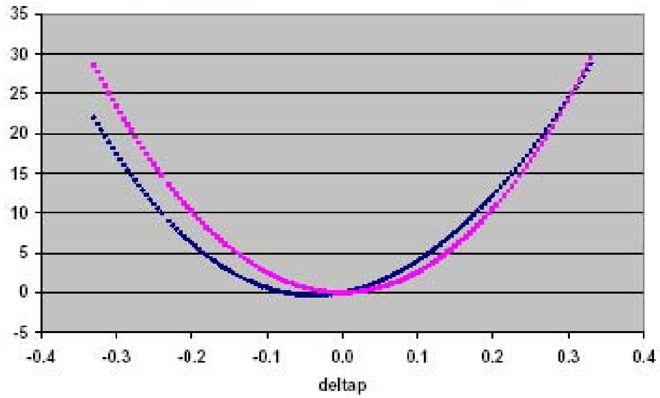
Tunes Q_x and Q_y vs. $\delta p/p$



Half apertures A_x and A_y in mm vs. $\delta p/p$



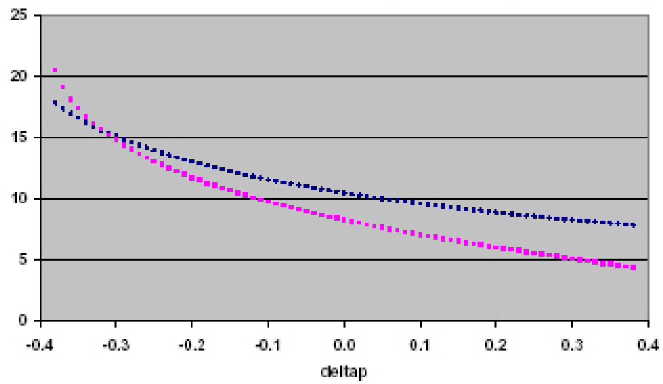
Path length $\delta(s)$ and travel time ct in mm



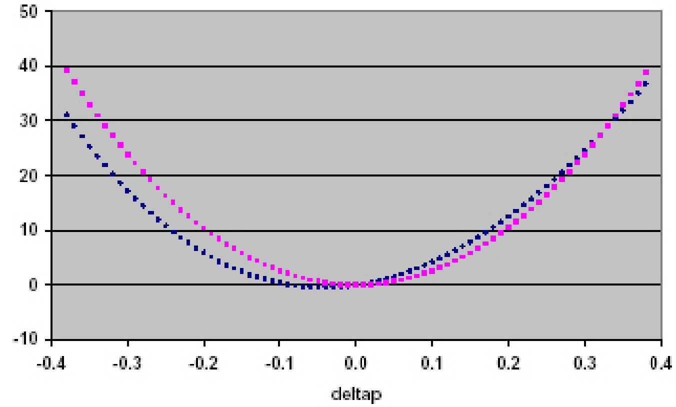
- Stable tunes q_x and q_y in range $-1/3 \leq \delta p/p \leq 1/3$
- $A_x < 20$ mm and $A_y < 10$ mm for $\varepsilon_n = 0.3$ mm, geometrical mean between ε_n in ATF and CLIC drive beam linacs
- Fit to ct yields $\eta_1 = 0.0167$

Triplet Figures

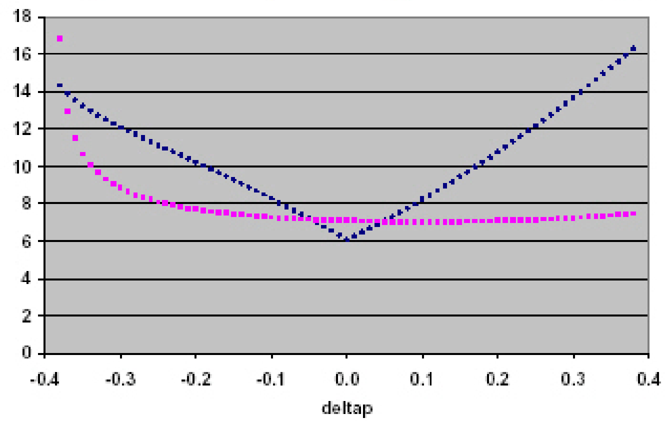
Tunes Q_x and Q_y vs. $\delta p/p$



Path length $\delta(s)$ and travel time ct in mm



Half apertures A_x and A_y in mm vs. $\delta p/p$



- Stable tunes q_x and q_y in range $-1/3 \leq \delta p/p \leq 1/3$
- $A_x < 20$ mm and $A_y < 10$ mm for $\varepsilon_n = 0.3$ mm, geometrical mean between ATF and CLIC drive beam linacs
- Fit to ct yields $\eta_1 = 0.0149$

Specifications of Triplet Parameters

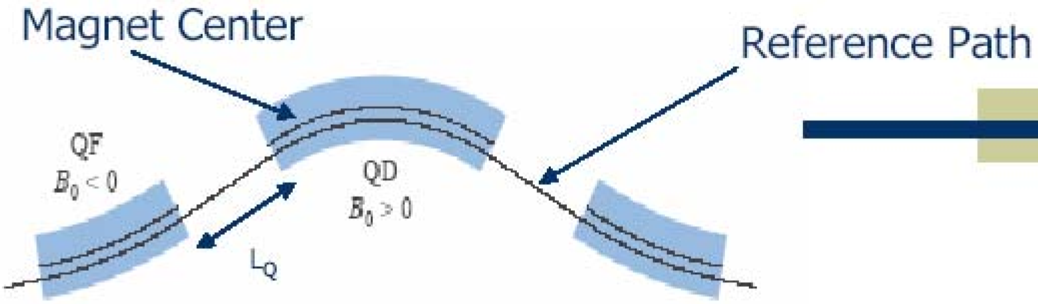
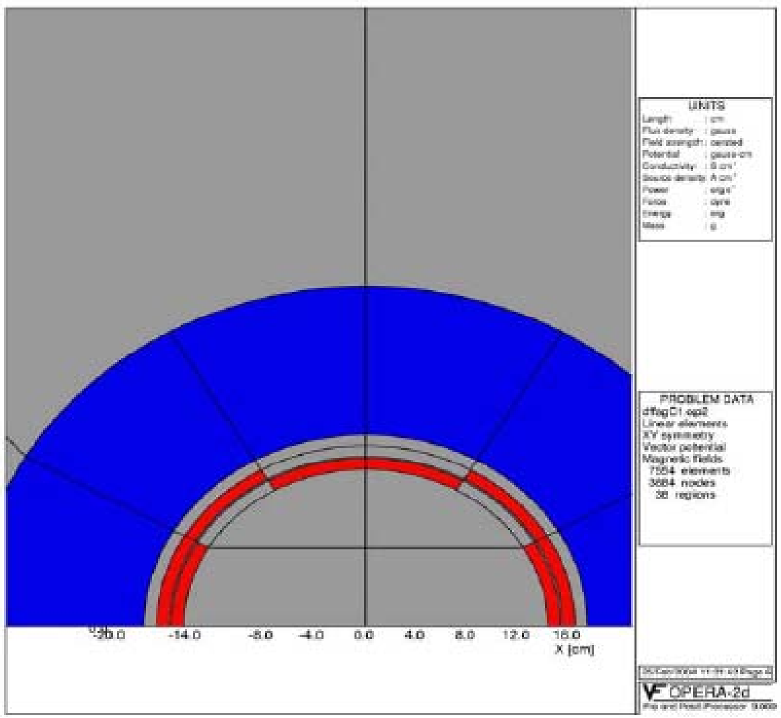


Figure 1: Geometry of the triplet. The displacements of the magnet centers for all magnets are positive. The solid line is the reference orbit, the dot-dashed line goes through the center of the magnet aperture.

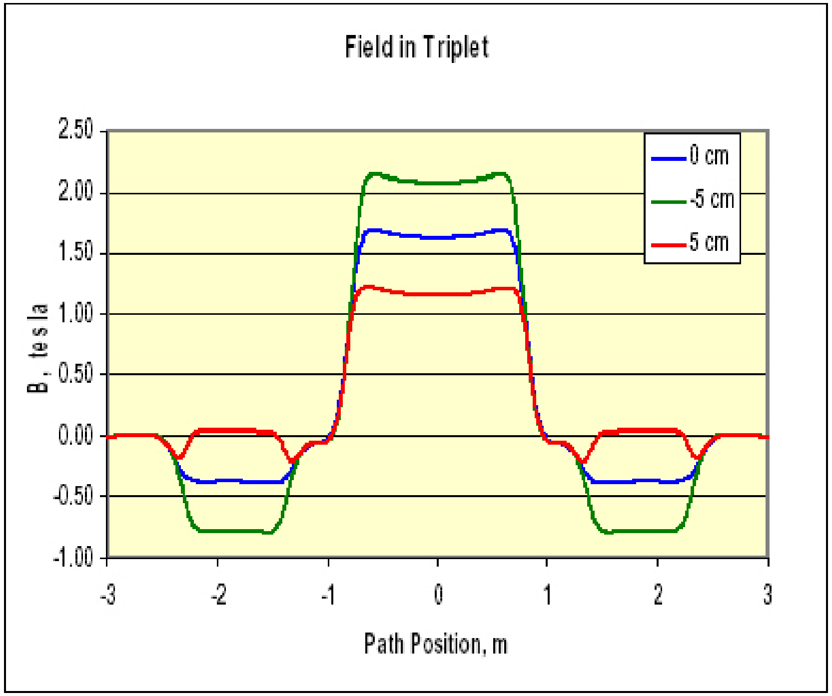
E_{mean} (GeV)	7.5		15	
E_{min} (GeV) E_{max} (GeV)	5 10		10 20	
L_0 (m) L_Q (m)	2 0.5			
Numb of Cell	90		105	
	QD	QF	QD	QF
L_{eff} (m)	1.612338	1.0656	1.762347	1.275747
ρ (m)	15.274	-59.6174	18.4002	-70.9958
x_0 (mm)	-1.573	7.667	1.148	8.745
R_{aper} (cm)	14.0916	15.2628	10.3756	12.6256
B_0 (T)	1.63774	-0.41959	2.71917	-0.70474
G (T/m)	-9.1883	8.1768	-15.4948	12.5874

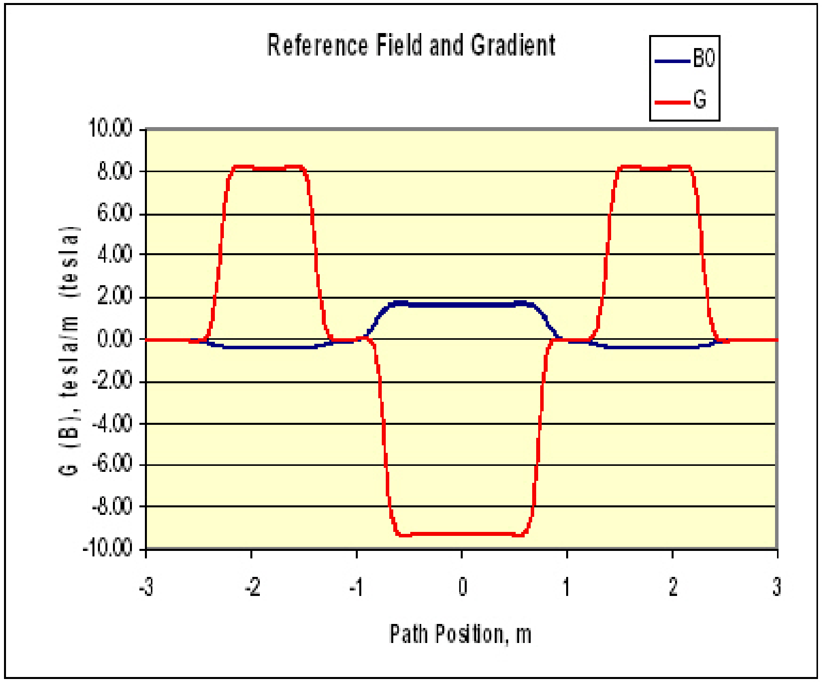
2D Cross Section of Magnet Model



- The figure shows the 2D cross section of a magnet that has both dipole and quadrupole coils.
- The yoke is just a simple iron annulus. In construction it would look more like the KEK FFAG cross section

Field and Gradient along the Reference Path





R&D activities on ADS and Proposal of China Spallation Neutron Source

Fang Shouxian

Institute of High Energy Physics, Beijing

2004.04

CONTENTS

- R&D Program of ADS (Accelerator Driven Sub-critical reactor)
- Preliminary Consideration on CSNS (Chinese Spallation Neutron Source)
- Summary

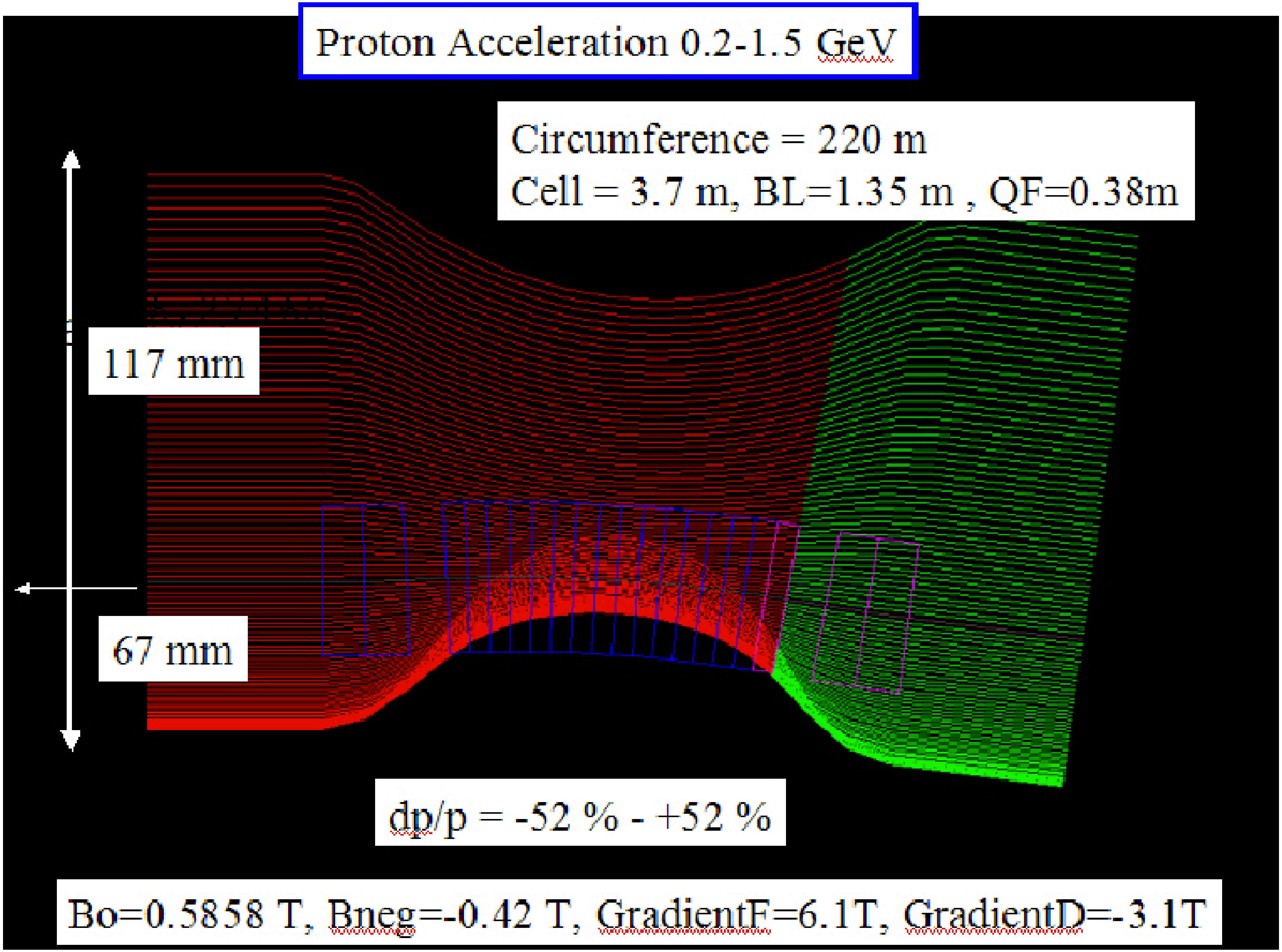
Prediction for future Energy Require

Need for Energy Source in 2030 in China (Standard Coal in Billion Ton)

Coal	2.7	Hydropower	0.3
Oil	0.17	Nuclear Power	0.5
Gas	0.22	Others	0.1

Total 4.0

Non-scaling FFAG



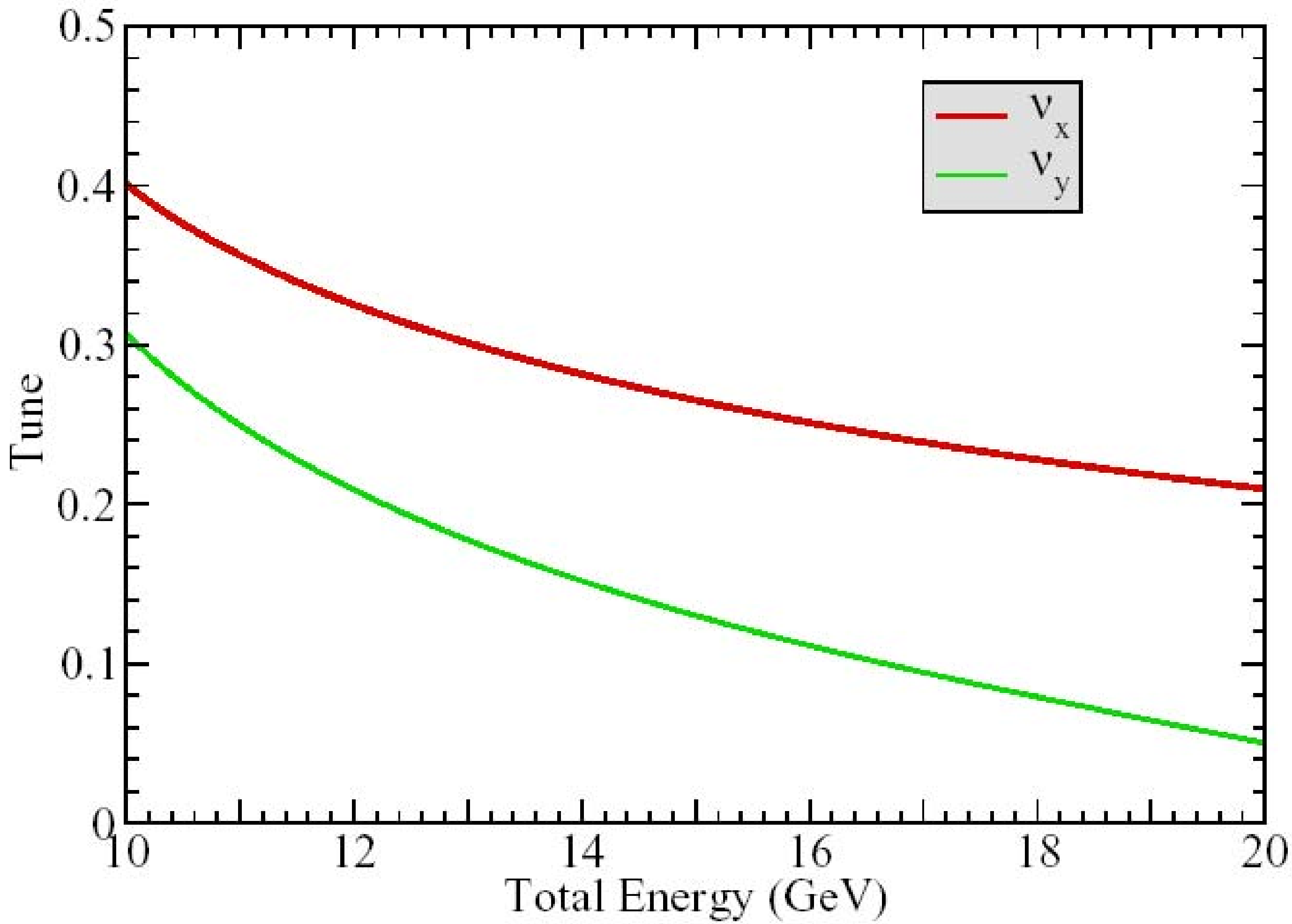
Scott Berg

Fix Pole Tip Fields (cont.)

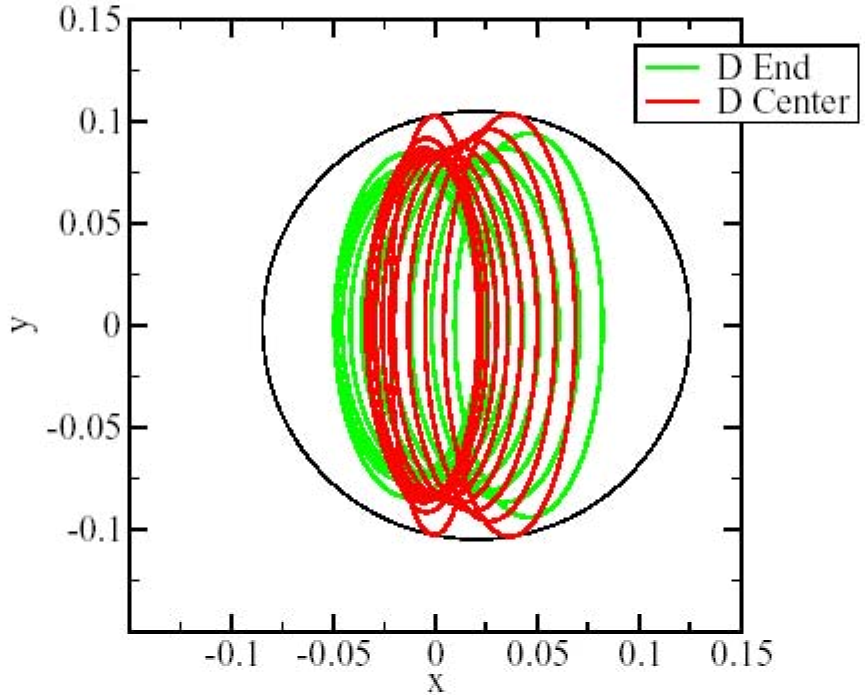
Type	FDF	FD	FODO
Cells	93	101	113
D Length (cm)	128	101	81
D Radius (cm)	8.4	6.9	8.0
F Length (cm)	45	81	60
F Radius (cm)	9.5	12.4	14.2
RF Voltage (MV)	698	758	848
$c\Delta T$ (cm)	19.9	21.6	24.1
Circumference (m)	481	436	612
Magnet cost (PB)	76	69	90
RF cost (PB)	45	49	55
Linear cost (PB)	12	11	15
Total cost (PB)	134	129	161

- Triplet has shortest time-of-flight and lowest voltage requirement
- Doublet has lowest cost
  - Fewer magnets than triplet
- FODO does poorly
  - Relatively long cell

Split Tunes

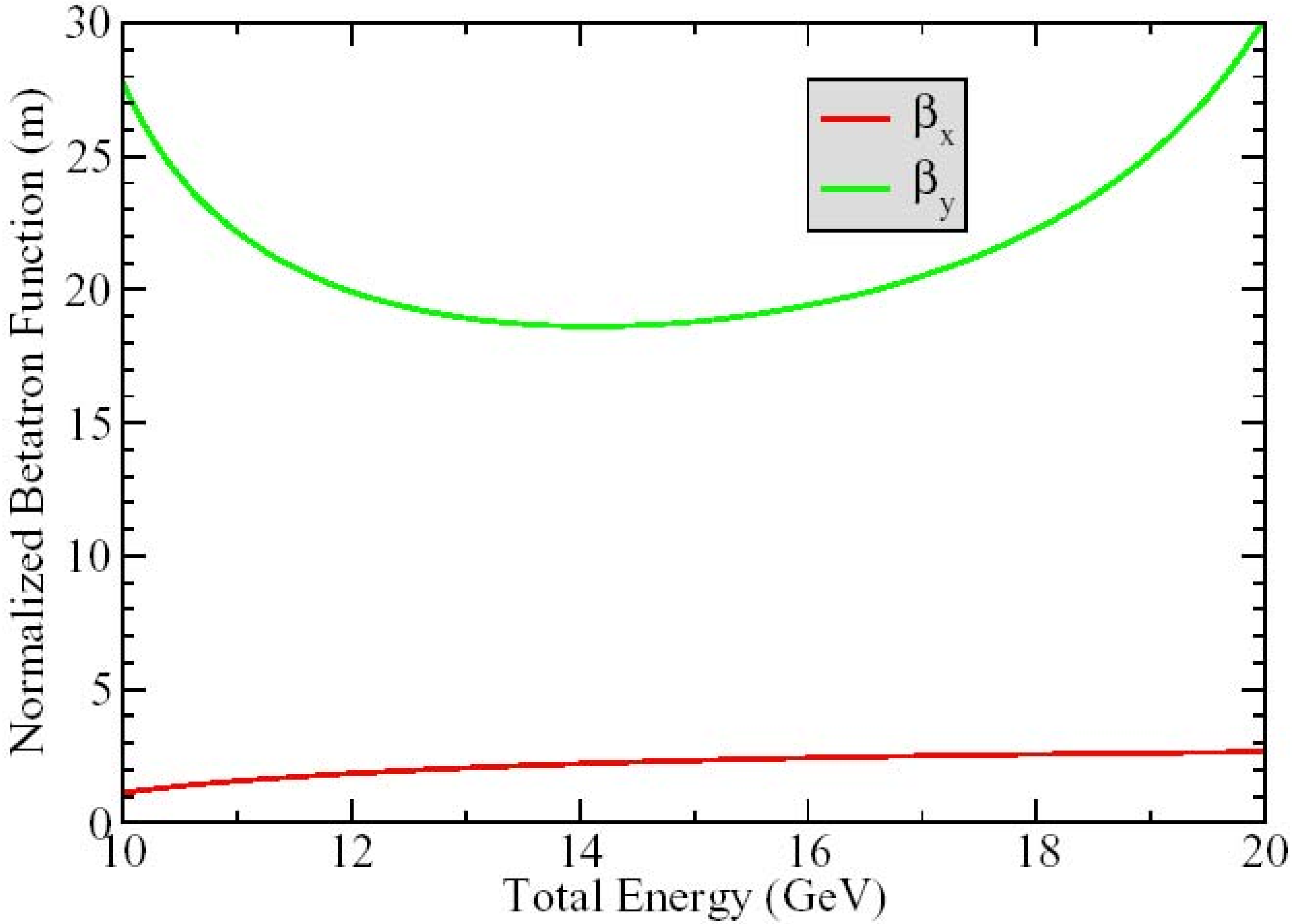


Optimized Tunes: Ellipses



Scott Berg

Optimized Tunes: Beta Functions



D. Kalchev

Building Taylor Maps with Mathematica and Applications to FFAG

Mathematica can handle Taylor series analytically.

All coeff. are numbers $\Rightarrow$ numerical map.

For now only 4D map:

$$X_f = :\mathcal{M}:X|_{X=X_0} = e^{:F_{conc}:}R_{tot}.X|_{X=X_0}$$

X_0=initial vector; X_f=final vector.

Phase sp. vector: X=(x, p_x, τ, p_τ) – deviations from ref. orb. with momentum p_0 and curvature $h(s) = 1/\rho_0(s)$.

Note: $:\mathcal{M}:$ is just 4 polynomial functions of the comp. of X (and in fact 3, because $p_t = const$)

Closed orb as fixed point (`FindRoot`)
tune by Jacobian at the fix.pt.
$c\tau$ directly from the 3-d polynom.

Fixed point is a solution $(x, p_x)|_{co}$ of the first two eqn. $X_f = X_0$ for a fixed p_t.

D. Kalchev

FFAG opt. elements: combined sect. bend B
quadrupole Q
drift D

$$1 \text{ cell} = (\textbf{Q-D-B-D-Q})$$

Field expansion: We assume field B_y changes in radial dir. linearly to sec. order in x and keep only cubic terms in A_s and H)

$$\frac{eA_s}{p_0} = -hx + \frac{1}{2}(k_1 + h^2)x^2 - \frac{1}{6}(hk_1 - 3h^3)x^3 + O(x^4)$$

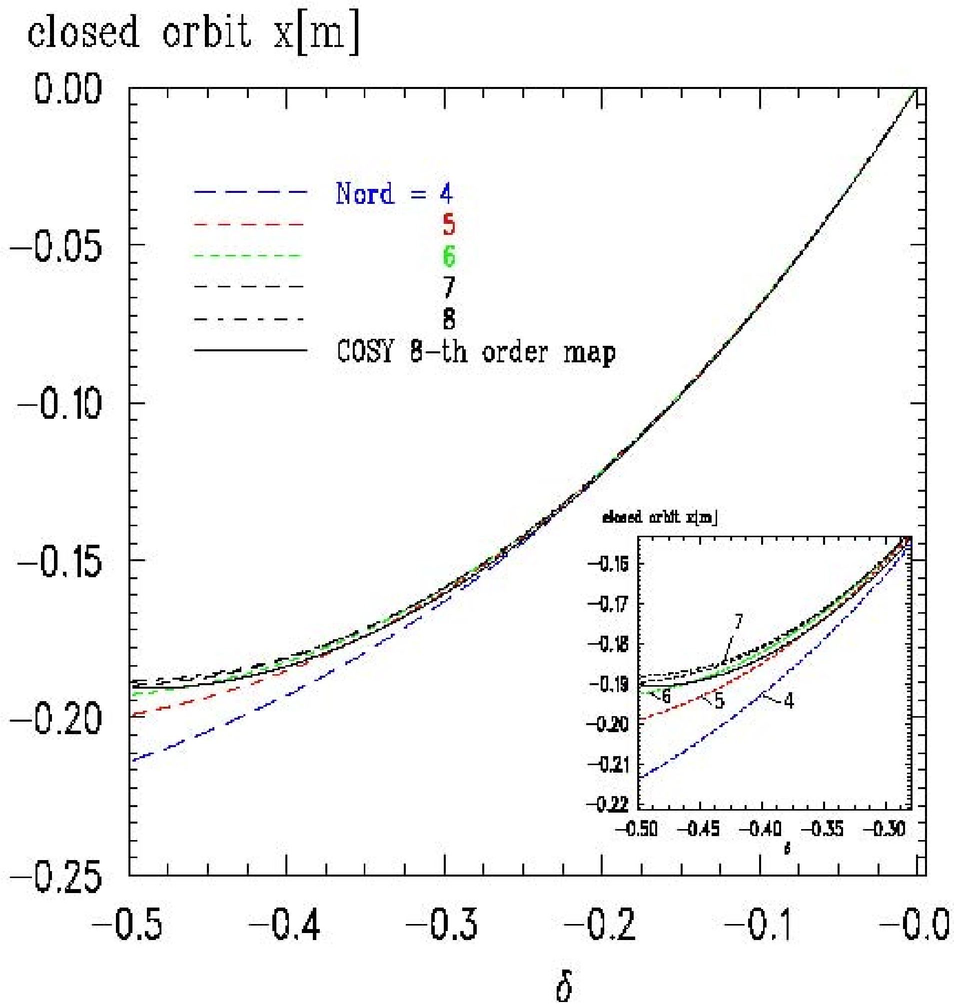
$$\frac{e}{p_0}B_y(x) = \frac{e}{p_0}\left(\frac{hA_s}{1+hx} + \frac{\partial A_s}{\partial x}\right) = -h + k_1 x + O(x^3)$$

The long. vect pot. is truncated to 3d order of x.

COSY uses a higher order expansion obeying LAPLACE – expect differences!

D. Kalchev

Comparisons: Lie algebra notebook and COSY



COSY script – orbit finder is a courtesy of
Dejan Trbojevic

Integer Resonances and Closed Orbit Distortions (in synchrotons)

Maybe related to resonances crossing in FFAG synchrotrons

T. SUZUKI (KEK)

FFAG workshop at TRIUMF

- Based on my elementary lectures at IHEP. Beijng, and JAERI, TOKAI
- Y. MORI's question
  Integer resonance – $x_{co} \to \infty$
  difficult to understand intuitively
  – initial-value problem ?
- ~~Synchro~~ Synchro betatron coupling by Dispersion → Satellite of integer → large D

$$X = A\cos\nu\phi + B\sin\nu\phi$$

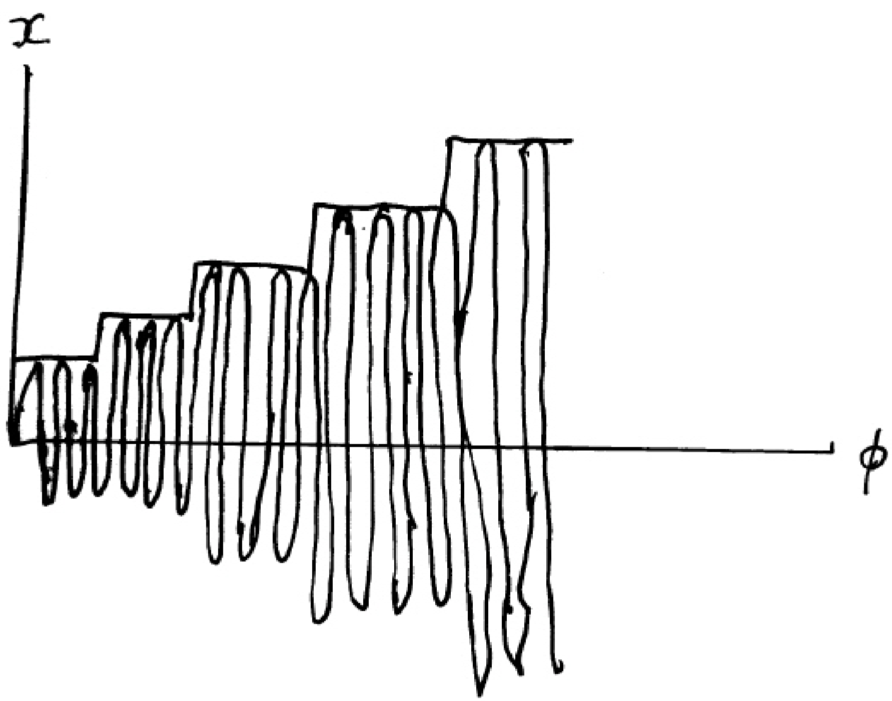
$$= \sqrt{A^2+B^2}\ \cos(\nu\phi + \psi)$$

rapidly oscillating

slow function of ϕ

↓

old resonant perturbation theory



T. Suzuki

Particular Solution

$$X = X_{co} - X_{co} \cos 2\pi\nu N - P_{co} \sin \pi\nu N$$

$$P = P_{co} - P_{co} \cos 2\pi\nu N + X_{co} \sin 2\pi\nu N$$

zero for $N=0$ / initial value

general solution of homogeneous equation

$$X_h = X_0 \cos 2\pi\nu N + P_0 \sin 2\pi\nu N$$

$$P_h = -X_0 \sin 2\pi\nu N + P_0 \cos 2\pi\nu N$$

$$X = X_h + X_{co}$$

$$= \underbrace{(X_0 - X_{co})}_{X_{\beta o}} \cos 2\pi\nu N + \underbrace{(P_0 - P_{co})}_{P_{\beta o}} \sin 2\pi\nu N + X_{co}$$

$$P = P_{co} + \underbrace{(P_0 - P_{co})}_{P_{\beta o}} \cos 2\pi\nu N - \underbrace{(X_0 - X_{co})}_{X_{\beta o}} \sin 2\pi\nu N$$

FFAG 2004 SUMMARY

- General FFAG aspects
- High-intensity proton drivers
- Muon accelerators
- Muon cooling
- Electron model
- Technical considerations
- Public relations, politics, funding
- Next workshop

General FFAG Aspects

- We shall not investigate full continuum of machines.
- Rather: 2 extremes and 1 particular intermediate:
    - scaling (fixed tune, non-linear fields)
        - fixed tune, non-scaling (non-linear fields)
    - variable tune, non-scaling (linear fields)
- Find names which will be better understood outside our group.

e.g. scaling FFAG, flat-tune adjusted-field FFAG, variable-tune linear-field FFAG

- Analytic investigation of the linear non-scaling m/c is complete and should be published.
- Analytic work on the non-linear non-scaling machine needs to grow and continue (see Sandro's *to do* list).
- Analytic work on resonance crossing should continue.

High-Intensity Proton Drivers

- Time-line of ORNL SNS ruled out FFAG in favour of SC linac.
- Replacement of BNL AGS Booster gives another opportunity if we act quickly.
- Spallation source or waste burning device could be important application of FFAGs, as might be cancer therapy m/c.
- Who will work on 0.1-1 MW FFAG?
    - KEK has scaling m/c design for 1 GeV, 1 mA, 1 kHz
    - BNL has interest in Booster & RA
    - FNAL has interest in Booster & openings for students
    - IHEP has motive (spallation source) and opportunity window of 2-3 years.

High-Intensity Proton Drivers continued

- Identify relative merits and disadvantages of linac versus FFAG, (e.g space charge limits). But time-line is short. Who?
- Identify potential show-stoppers that arise when you move from 10 Hz to 1 kHz operation (e.g. powerful rf) Who?

Other Applications ?

- Cancer therapy machine in hospital environment
  - More beam due to higher repetition rate, more compact size – d.c. magnets can be SC, less maintenance (*c.f.* NMR), less expensive
  - Firm up this argument *c.f.* Loma Linda synchrotron, etc.
- Spec: 5 grey/minute at 250 MeV
- Move m/c intensity from "experimental" to "treatment" level
- Encounter space-charge limits
- KEK to set up "FFAG Project Office" as resource to consortium of industry and academia.

Electron Model continued

- Include controlled nonlinearity (but *one* element only).

Do not force model to face "manufactured" problems.

- PoP proton machine was critical for re-acceptance of scaling FFAG.
- Electron model will be instrumental for nonscaling case

R&D must be pushed to technical design addressing:

  - Injection (<10 ns rise time), Tunability
  - Alignment issues, Diagnostics
  - Permanent magnets vs. electric magnets
  - Engineering design, Cost estimates

- Different players are needed. How do we get them involved?
- Model needs a *home* with services e.g. BNL ATF
- *Bottom line* – model cannot fail; m/c must be tunable; cost implications for magnet design & power supply.